CRANFIELD UNIVERSITY

WASHINGTON CRISTOBAL ORTEGA JARRIN

SCALABILITY OF A ROBOTIC INSPECTION AND REPAIR SYSTEM

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
MSc by Research in Manufacturing

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Academic Year: 2019 - 2020

Supervisor: Andrew Starr
Associate Supervisor: Isidro Durazo
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This thesis is submitted in partial fulfilment of the requirements for the degree of Masters by Research
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

Shift2Rail and In2Smart are two initiatives that will be part of the development of the necessary technologies to complete the Single European Railway Area (SERA). The target of this proposal is to accelerate the integration of new and advanced technologies into innovative rail product solutions.

Shift2Rail has a robust framework to meet ambitious objectives. The most important is to double the capacity of the European rail system and increase its reliability and service quality by 50% while having life-cycle costs.

In2Smart, as a project directed mainly of Network Rail, is measured in Technology Readiness Levels (TRL). These levels will indicate the maturity of technology for the application into the industry. The intention of this project is to reach a homogeneous TRL 3/4 demonstrator of a system capable to secure proper maintenance of rails, which is a Robotic Inspection and Repair System (RIRS).

This research is focused on the scalability of the RIRS, taking into consideration the creation of a representative demonstrator that will authenticate the concept, the validation and verification of that demonstrator and finally the simulation of a scale-up system that will be more robust and will upgrade the TRL. This document contains the development of the control diagrams and schematics for the future incorporation of this control to a higher TRL prototype.

The initial demonstrator consists of an autonomous railway vehicle equipped with a robotic arm that will scan the rails searching for faults and simulate a repairing process with a 3D printed polymer. The V&V of the physical demonstrator was a result of tests in the laboratory and the display of the demonstrator in several conferences and events.

Keywords: Shift2Rail, In2Smart, TRL, V&V, RIRS, autonomous, scalability

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I would like to thank my parents who helped me a lot in gathering different information, collecting data and guiding me from time to time in making this project, despite their busy schedules, they gave me different ideas in making this project unique.

Thanking you,

Washington Ortega

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

No table of equations needed.

LIST OF ABBREVIATIONS

IT	Information Technology
ACS	Autonomous Control System
ALARP	As Low Aas Reasonably Practicable
AsBO	Assessment Body
C2	Command and Control
CAN	Controller Area Network
COTS	Common Safety Method
CSM	Digital Imaging for Condition Asset Monitoring System
DIFCAM	Designers Risk Assessment
DRA	Engineer’s Line Reference
ELR	Common Safety Method
EMC	Electro-Magnetic Compatibility
ETCS	European Train Control System
GSM-R	Global System for Mobile communications - Railway
GRIP	Governance for Railway Investment Project
HAZID	Hazard identification (risk analysis)
HBW	High bandwidth
HoS	Health of system
LoS	Life of the system
MoE	Measure of effectiveness
MoP	Measure of performance
MoS	Margin of safety
NoBo	Notified Body
NR	Network Rail
ORR	Office of Rail and Road
PEM	Programme Engineering Manager
PHL	Project Hazard Log
PHR	Project Hazard Record
PS	Payload System
PSS	Payload System Safety
RCM	Remote Condition Monitoring
RDMS	Rail Defect Management System

RHR	Rail Head Repair
RIRS	Robotic Inspection and Repair System
ROC	Rail Operating Centre
RSSB	Rail Safety and Standards Board
SOA	Safe Operating Area
SMIS	Safety Management Information System
SORAT	Signal Overrun Risk Assessment Tool
TBD	To Be Decided
TID	Track Identification
TIM	Tunnel Inspection Module
UTU	Ultrasonic Test Unit
VS	Vehicle System
VSM	Vehicle System Manager
VSP	Vehicle System Platform
CCS	Command and Cotrol System
GPS	Global Positioning System
IAMS	Intelligent Asset Management Strategies
R&I	Research and Implementation
ROS	Robot Operating System
TD	Technological Demonstrators
TRL	Technology Readiness Level
TSC	Transport System Catapult
V&V	Validation and Verification
WP	Work Package

1 Introduction

There is a drive within the wider rail industry to reduce the exposure of personnel to trackside work and the risks associated with this, according to the annual national statistics in rail safety for the UK, there have been 6,247 injuries on the workforce on the Mainline, of which 158 were major injuries, in the period 2018-2019. These results are 3.1% lower than the ones obtained in the previous year (Rail, 2018). The reduction in the injuries of the personnel was obtained by the implementation of robust technologies and detailed Health and Safety procedures. By undertaking inspection and repair procedures with an operator supervising remotely, away from the trackside, or even autonomously, this exposure can be reduced.

Figure 1 Worker Injuries on the UK Mainline (Rail, 2018)

As the use of data for predictive maintenance increases, there is a greater demand for the inspection data to be repeatable and consistent. By employing elements of automation, the repeatability of the inspection process can be increased. Taking into consideration that the role that humans have been playing so far in a maintenance environment is rapidly changing towards the new Industry 4.0, the rail business has to look forward to innovative solutions to keep competitive.

The forecasted increase in traffic on the rail network will lead to an increase in inspection frequency and repair activity, which is unlikely to be met by a sufficient increase in personnel to undertake these activities. According to the Annual Statistical Release for Rail Usage in the UK, all regions, except for the South West, saw an annual increase in journeys to/from other regions, with a national increase of 1.2% (Road, 2019). This increase in the network traffic will also limit opportunities for activities that require a possession to take place.

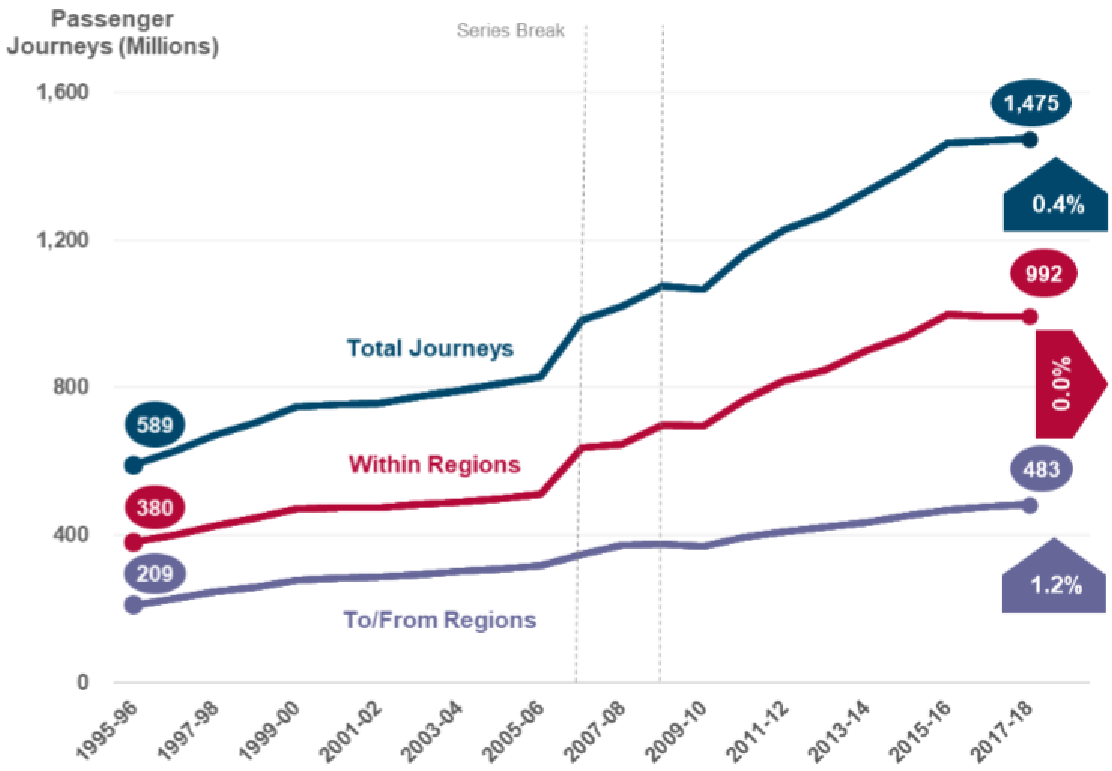

Figure 2 Passenger journeys (millions) to/from and within regions, Great Britain,1995-96 to 2017-18 and percentage change from 2016-17 to 2017-18 (Road, 2019)

Robotics is one area of development that enables great opportunities for solving the challenges presented before. The industrial robot sales have increased for the last five years. The Executive Summary of World Robotics for 2019 stands that in 2018 global robot installations increased by 6% to 422,271 units installed, worth about USD 16.5 billion and is forecasted to continue the same growth path, this according to the International Federation of Robotics (IFR) (Worldrobotics, 2019). Historically, the tasks undertaken by robots were unhealthy, hazardous or/and monotonous (Williamson, 2019). As technology develops and matures, new opportunities for robotic deployments are presenting themselves in fields such as healthcare and service robots. Fixed robotic arms offer flexibility and excel at a repetitive task in controlled environments, however, they are limited by being attached to a static base. Combining a mobile base with a manipulator such as a robotic arm, the work area is limited by where the mobile base can access. Mobile robot locomotion can be achieved by wheels, tracks, even lead on the ground, with air-based or water-based robots.

To solve the problem outlined several projects and suggestions were proposed. Shift2Rail is one of them that aims to innovate in the rail industry by the implementation of new technologies and here is where In2Smart comes. These two proposals were made by Network Rail to find a pioneering solution based on new technologies.

As a solution for the inspection and repair procedures in the railway a Robotic Inspection and Repair System (RIRS) was proposed by these mentioned initiatives. This mainly bases on a vehicle agnostic Command and Control System (CCS). Part of the development of this technology is to prove that it will be fit the needs of the rail industry and will comply with the requirements to solve the problems mentioned before.

To test that the RIRS and the CCS are suitable and are relevant for the industry a virtual environment was elaborate was developed using ROS (Robotic Operating System) and the core elements of the RIRS were simulated in an open-source software named Gazebo. The software in the loop was the term used to refer to this demonstrative part of the concept.

The RIRS is intended to be agnostic to the vehicle it is on, but due to simulation purposes a road-rail vehicle was chosen. The software has a simulated GPS sensor, scanning laser range finders and a camera on the end of a robotic arm. The software in the loop is capable of simulating the RIRS navigating to its destination by controlling speed and detecting obstacles on the way and the robotic arm can follow trajectories to represent: railhead inspection, additive manufacturing repair and bolt fastening patterns.

To supplement the virtual model, a physical concept demonstrator for the Robotic Inspection and Repair System was created. This physical concept was design to provide a real demonstration of the RIRS capabilities, making it more realistic, and helping to understand the challenges that such systems will be facing in the real environment, this challenges cannot be seen on a simulated environment as there are too many variables that have to be taken into consideration to have a good representation of it.

The physical demonstrator is capable of performing the following 4 operations: autonomous fault search, simulated repair with a robot arm mounted end effector, communication with a remote user and recovery to base. The RIRS vehicle is a battery-powered train that runs on a 5' (127mm) gauge rail and is approximately 1/11 scale of real railway infrastructure. The CCS developed in ROS for the virtual demonstrator was adapted to Arduino/Raspberry controllers to simulate the CCS. The demonstrator operation follows the following phases autonomously: fault search; find the fault location; make a simulated repair and return to base.

The purpose of the simulation and the physical demonstrator is to test, validate and verify the capabilities of the Command and Control System. The CCS was designed to create a system that can give a level of autonomy to whatever vehicle and robot it is running, for this, the principle was to see if the technology is suitable and useful to the rail industry and to do this TRL's (Technology Readiness Levels) were used. These levels are a method to measure the maturity of technology during the acquisition phase (Clausing & Holmes, 2010). The aim is that in the future, this will be further tested using a large robot equipped with a robotic arm in a representative environment that increase the TRL.

This document will present the scalability of a Robotic Inspection and Repair System (RIRS), focusing on the demonstrator created by Cranfield University and software in the loop developed by Transport System Catapult. Both elements are a key factor for the production of the scalability of the RIRS.

1.1 Background

To understand the main purpose of this project is important to know where it comes from and the initiatives behind it. That is why in this chapter will be an introduction of the two most important initiatives, like Shift2Rail and In2Smart, which sets the starting point for this project.

Also is important to clarify the position of Cranfield University in this project and what was commissioned to develop in collaboration with the initiatives mentioned before.

1.1.1 Shift2Rail

Shift2Rail focuses on the research and innovation (R&I) in new technologies applicable in the rail industry. This is the first European initiative that accelerates the integration of advanced technologies into innovative rail product solutions. This initiative increases the effectiveness of the European rail industry to meet the changes in the EU transport needs, taking into consideration the Horizon 2020 proposition to develop advanced technology to complete the Single European Railway Area (SERA).

Shift2Rail helps to boost the rail supply industry’s competitive edge, introducing new market perspectives and offering significant employment and export opportunities.

The world leadership of the European railway manufacturing industry is being challenged by new market entrants, especially those from Asia offering attractive products at low acquisition costs. The best response to this competitive challenge is through innovation to improve product quality and reliability from day one by reducing life-cycle costs, combined with a railway system approach. Public and private investment in Shift2Rail also have a multiplier effect on the industry investment required to bring such products to the marketplace, and on expanding market opportunities for European industry, both in Europe and overseas. It also helps to overcome some of the present EU rail market shortcomings, namely fragmentation of production, insufficient collaboration and partnership across the rail industry, differing operating procedures among rail users, limited standardization and low-efficiency levels.

Railway undertakings, infrastructure managers and public transport operators also benefit from innovations that drastically reduce infrastructure and operating costs. This also helps to cut down on subsidies paid out by national governments estimated at between EUR 36 billion and EUR 38 billion in Europe in 2012.

Passengers and freight service users will benefit from a step-change in the reliability and quality of services. Improved competitiveness and attractiveness of rail services, combined with increased capacity, will help rail take on an increased share of transport demand, thereby contributing to the reduction of traffic congestion and CO2 emissions. Citizens' health and well-being will also benefit, thanks to reduced noise pollution from the rail. (Shift2Rail, 2019)

1.1.2 In2Smart

IN2SMART addresses the "Intelligent Maintenance Systems and Strategies" call launched by the Shift2Rail. IN2SMART delivers an Intelligent Asset Maintenance System, creating new and optimized strategies, frameworks, processes and methodologies, tools, products and systems for the implementation of a step-change in risk-based, prescriptive and general asset management in the rail sector.

The IN2SMART overall objectives are to make advances towards achieving the global SHIFT2RAIL objectives of:

- Capacity: enhancing the existing capacity to match user demand of the European rail system
- Reliability: delivering improved & more consistent quality of service
- Life cycle cost: reducing LCC & hence increasing competitiveness of the European rail industry.

This is being achieved dealing with asset management and by the implementation of a whole system approach that links together Railway Information Measuring and Monitoring System (RIMS), Dynamic Railway Information Management System (DRIMS) and Intelligent Asset Management Strategies (IAMS).

More in detail, IN2SMART was born in the context of a growing demand for a step-change in asset management to be delivered through innovative technologies, new economic possibilities, and enhanced legislative standards in the rail sector. It wants to contribute to creating new and optimized strategies, frameworks, processes, and methodologies, tools, products and systems for the implementation of a step-change in risk-based, prescriptive and holistic asset management in the rail sector. To do this the project is structured in the three former Technological Demonstrators (TD):

- TD3.7 Railway Information Measuring and Monitoring System (RIMS) that focuses on asset status data collection (measuring and monitoring), processing and data aggregation producing data and information on the status of assets;
- TD3.6 Dynamic Railway Information Management System (DRIMS) that focuses on interfaces with external systems; maintenance-related data management and data mining and data analytics; asset degradation modeling covering both degradation modeling driven by data and domain knowledge and the enhancement of existing models using data/new insights;
- TD3.8 Intelligent Asset Management Strategies (IAMS) that concentrates on decision making (based also but not only on TD3.6 input); validation and implementation of degradation models based on the combination of traditional and data-driven degradation models and embedding them in the operational maintenance process based upon domain knowledge; system modeling; strategies and human decision support; automated execution of work.

The entire project scope is to aim towards an intelligent asset management systems (IAMS) according to ISO 55000; taking into consideration that IN2SMART is the first step only aiming to reach TRL4-5 results (In2Smart & Systems, 2016).

The complete structure of the project can be seen in the following figures, where there are different Work Packages (WP) that have to be completed:

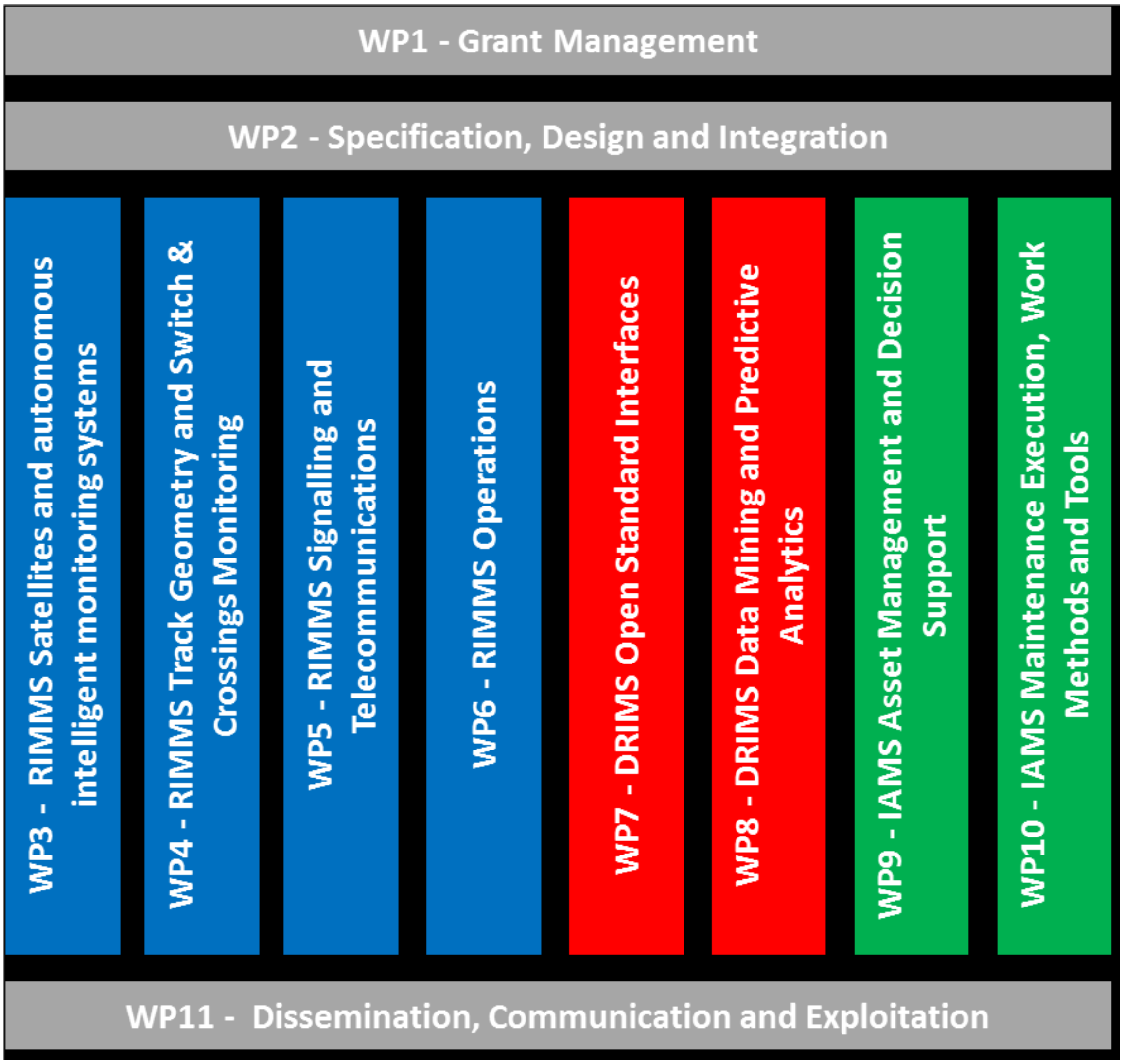

Figure 3 In2Smart project structure (In2Smart, 2016)

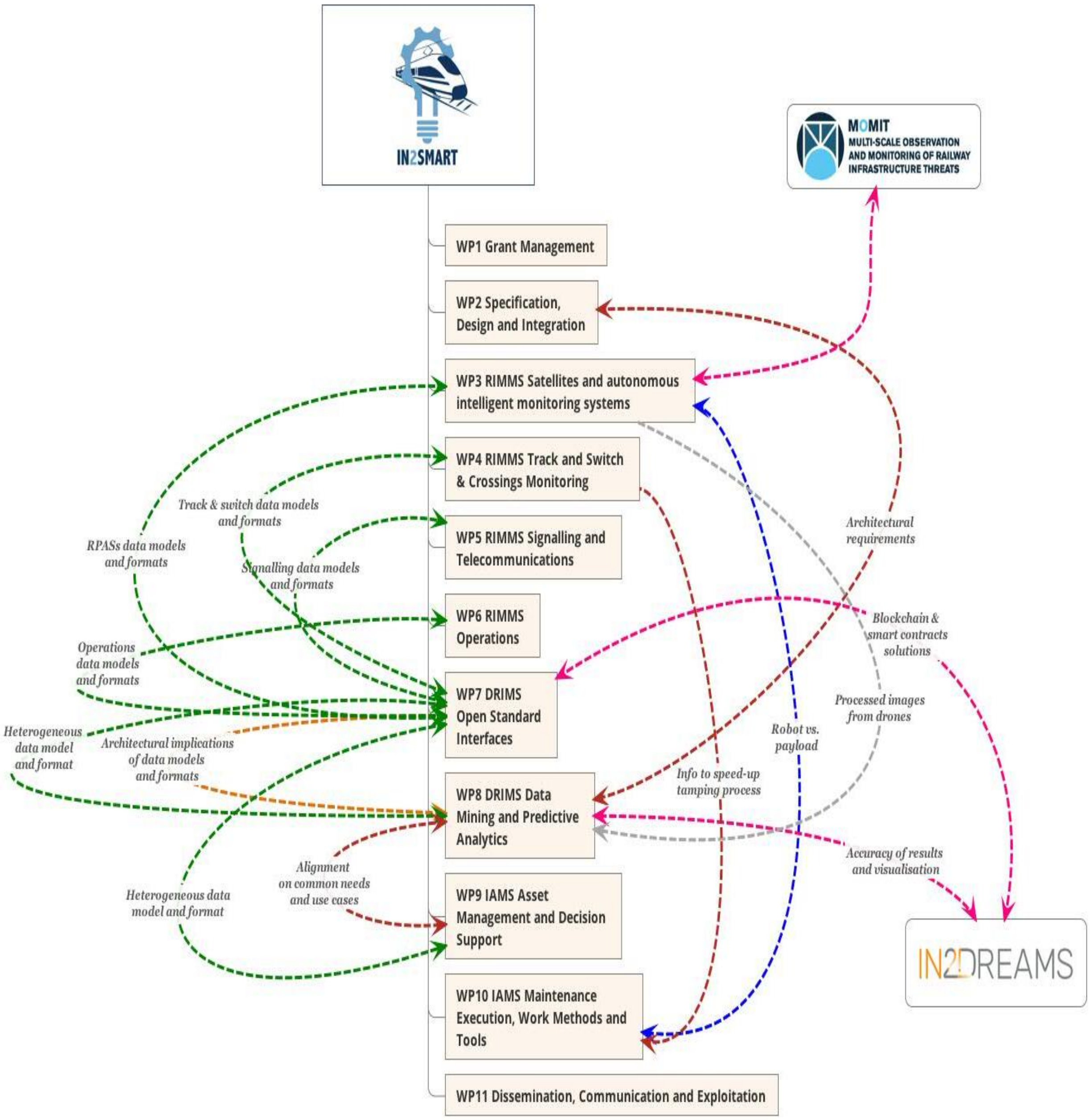

Figure 4 In2Smart mind map (In2Smart & Systems, 2016)

This project is mainly focused on the development of the work package 10 ‘Intelligent Asset Management Systems (IAMS) maintenance execution, work methods, and tools’. To achieve WP10 the creation of a Robotic Inspection and Repair System (RIRS) was proposed, this system has to be validated and verify to achieve the corresponding TRL’s proposed for this initiative.

1.1.3 RIRS definition

The present railway maintenance is manual labor intensive, whereas the future should be largely automated with robotic technologies. Several experimental robots have been recently developed. These robots are mainly used for rail inspection using a range of sensing technologies that include ultrasonic sensors, thermographic sensors, and eddy currents. However, if an autonomously operating robot will perform not only inspection tasks but also physical repair tasks, this will certainly be a breakthrough.

Having researched on this will help to develop and demonstrate concepts of robotic maintenance systems. To do so, the project develops a physical demonstrator that can showcase automated inspection and repair of railway physical assets. The demonstrator should be not only used in a lab environment but also scale it up in order to be working on a real industry environment.

The robotic inspection and repair will be a machine that includes:

- A railway carriage or mobile unit capable to travel along the rails.
- Fitted instrumentation capable of searching for and finding a simple “fault” that for testing proposes will be simulated.
- A robotic arm on top of the mobile unit, fitted with an end-effector capable of performing any simulated “repairing” procedure for the fault.
- A monitor to display the key steps through which the controller is progressing.

In order to achieve this, the RIRS should meet:

1. Defined scope and requirements of maintenance tasks the RIRS should perform.
2. Established maintenance processes.
3. Developed computer-based simulator of a demonstrator to design the simulator
4. Validation of the maintenance processes that cover a physical demonstrator and a simulation with a command of a control panel.

5. System design.
6. Development of a physical demonstrator capable to show the abilities of this technology and gives a general idea of its limitations and challenges.
7. Demonstration of actual maintenance tasks for validation of the concept.

1.2 Research scope

This research will examine collaborative robot ("cobot") deployment into the railway industry. This will result in a complete report that will help Network Rail become an expert customer and help define future cobot requirements. After the review, the preparation of a bench-top scale demonstration of safe human-robot collaboration principles will be completed. It is anticipated that the project will use existing cobots within the Manufacturing Informatics lab to achieve this.

The scope of the project is to have a clear idea documented that settle down the parameters for the integration of this system into bigger scales and more important answer the question: "Is this type of robot the solution for the rail industry future problems?"

Researching with the idea of proving the concept of a cobot working on the railways and knowing this will contribute on the deliverable: 'Remote Command and Autonomous System Architecture System Design Proposal' in the framework of the project titled 'Intelligent Innovative Smart Maintenance of Assets by integrated Technologies' (Acronym In2Smart; Grant Agreement no: 730569) within the wider Shift2Rail Programme. Where stands that overall objective of Work package 10, 'Intelligent Asset Management Systems (IAMS) Maintenance, Execution, Work Methods and Tools' is to develop technologies that will enhance the execution of both the integrated inspection and tamping process and robotic maintenance execution.

For this, the need for a physical demonstrator to present, validate and verify the viability of these types of technologies onto the rail industry, is needed. This demonstrator will follow the normal NR procidures of new product development and will be created with the idea of implementing it in an industrial environment.

The mentioned before defines the path that this research follows that will be:

1. Finalizing the physical demonstrator
    a. The demonstrator was an 80% finished at the time this project begin all the specifications and elements were selected before by National Railway and Cranfield staff.
    b. The contribution was to generate a control integration between the parts already adquire and finalizing the prototype.
2. Apply validation and verification methods
3. Compile results and add changes obtained
4. Apply upgrades to the design
5. Iterate

As a result of the research a serial of works have to be delivered:

- A scale demonstrator capable of:
    - Autonomous fault search and detection on a railway.
        - The faults will be representative as for the intention is to have a control system ready to implement in a higher TRL prototype that will incorporate it's own fault detection system.
    - Autonomous fault repair, using 3D printing.
        - As the faults this is a demonstrative method that will validate that the control system will be able to perform a repair on the tracks.
    - Be suitable for exhibition environments
- A V&V report of a simulated interface and a physical demonstrator.
- A scalability method that will give the demonstrator the possibility to advance into the industry and establish.

1.3 Aim and objectives

Aim:

Scale the Robotic Inspection and Repair Control System from a basic TRL3 to a TRL 4/5 upgrading it into an industrial-size level, demonstrating the possibilities and challenges in the control that the incorporation of this system generates to the industry in the nearest future.

Objectives:

- Conlude the basic scale physical demonstrator of the RIRS capable to perform tests to comprehend the ability of such a system; remarking its benefits and compiling its challenges for further corrections.
- Generate verification and validation methods composed by:
  - Physical tests to certify the integration of these types of robots into the industry.
  - Software simulations capable to accomplish different disturbances not only on the control but on the performance of the robot to see its limitations and weak point to correct
- Establish a method to scale the physical demonstrator to an industrial level capable to accomplish all the requirements generated from the main conflict the rail industry face. The concept will be facing the same procedure of V&V to confirm it is suitable.

1.4 Contributions

The main contribution is to scale the control framework form a TRL3 to a TRL4/5 based on the definition of the TRLs provided by Network Rail (Appendix) This control framework is ready to be implemented in a robust system upgrading from a basic microcontroller like Arduino and Raspberry PI to an indrustrial enbibed system, the system selected can be seen in chapter 6.

Also a contribution is to conclude the work made on the physical demonstrator as this was an 80% done by the time this thesis commence. The incorporation of the several systems already adquire from Cranfield and Network Rail. It was an important contribution as from this demonstrator this thesis adquire information to scale the control system and the RIRS.

Validating and verifying the complete physical demonstrator is a contribution to the understanding of the behaviour of the system and also identifying the challenges that a robot like this will face when scalling it.

2 Literature review

Reliability, that is, punctuality and safety, are important aspects of railway transport. The quality of the railway infrastructure has a major influence on the reliability of the railway system as a whole. Therefore, there must be enough preventive maintenance of the infrastructure (eg rail, ballast, sleepers, switches and fasteners). (X.Gibert, 2007) However, maintenance is expensive and time consuming that's why new technologies are designed to solve maintenance on railways. So it is important to reduce the maintenance time without reducing the maintenance itself (Shekhar, Shekhar, & P, 2015).

The research of automatic systems capable to detect faults and have the ability to autonomous repair it is one of the multiple ideas implanted in the In2Smart project, this project represents the first proposal of the Shift2Rail members referred. The Technological Demonstrators will deploy an overall concept for Intelligent Asset Management based on the following three main interlinked layers:

- Measuring and Monitoring systems to collect data from the field related to the railway assets status: IN2SMART will develop unmanned systems for "remote" monitoring; track geometry, switches & crossings and signaling monitoring systems; innovative measurement of train parameters and wheel defects combined with rolling stock identifications systems.

- Data management, data mining and data analytics procedures to process data from the field and other sources: IN2SMART will develop standard open interfaces to access heterogeneous maintenance-related data; analytic tools to automatically detect anomalies, discover and describe maintenance workflow processes and predict railway assets decay towards prescriptive maintenance.

- Degradation models and decision-making tools to support maintenance strategies and execution: IN2SMART will lay the foundation of a generic framework for asset management and decision support process. This framework will specify the scope, objectives, workflow, and outcomes of the decision-making process for maintenance intervention planning, and will be the enabler for the development of future decision support tools and systems. IN2SMART will also develop an optimized tamping tool and a robot platform for maintenance works. (In2Smart, 2016)

In order to have new technologies not only the inspection but also in the contribution of the physical repair process of railways a Robotic Inspection and Repair System was proposed.

2.1 Robot

Robotics has achieved its greatest success to date in the world of industrial manufacturing. Robot arms, or manipulators, comprise a $ 2 billion industry. Bolted at its shoulder to a specific position in the assembly line, the robot arm can move with great speed and accuracy to perform repetitive tasks such as spot welding and painting. In the electronics industry, manipulators place surface-mounted components with superhuman precision, making the portable telephone and laptop computer possible. Yet, for all of their successes, these commercial robots suffer from a fundamental disadvantage: lack of mobility. A fixed manipulator has a limited range of motion that depends on where it is bolted down. In contrast, a mobile robot would be able to travel throughout the manufacturing plant, flexibly applying its talents wherever it is most effective.

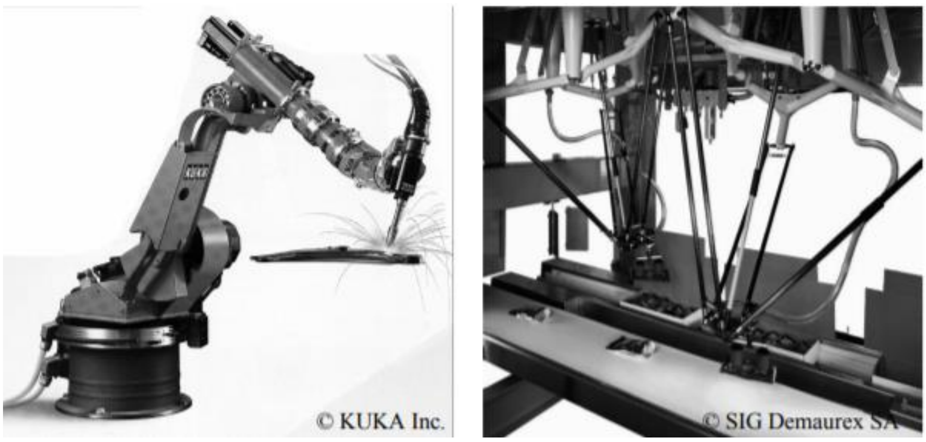

Figure 5: Picture of auto assembly plant-spot welding robot of KUKA and a parallel robot Delta of SIG Demaurex SA

But before going into the types of robots it is important to define what is considered a robot and what will be its meaning in this paper.

A robot is a machine especially one programmable by a computer capable of carrying out a complex series of actions automatically. (Oxford, 2018), robots can be guided by an external control device or the control may be embedded within. Robots may be constructed on the lines of the human form, but most robots are machines designed to perform a task with no regard to their aesthetics. Robots can be autonomous or semi-autonomous with a wide range of applications and functions.

For the purposes of this paper, a robot will be an autonomous machine, programmable to perform a serial of actions to suits the requirements previously established.

The two types of robots that concern to this research are the mobile robots and the robotic arms. These two different types of robots have a special characteristic that combining them can cause different issues in terms of locomotion and accuracy of the entire system. This generates the question "how can a mobile robot move unsupervised through real-world environments to fulfill its tasks?" The first challenge is locomotion itself. How should a mobile robot move, and what is it about a particular locomotion mechanism that makes it superior to alternative locomotion mechanisms? These questions should be solved by the research on the different sensors that are applied to the locomotion of mobile robots.

2.2 Current technologies on the railway inspection and repairing process.

As said before, monitoring the condition of railway components is essential to ensure train safety. Some experimental sensors and ways to inspect the railways have been recently developed (United States Patent No. US8660698B2, 2011), unfortunately, the repairing process is not included which leads to a gap for this research to cover.

2.2.1 Actual inspection systems.

Nowadays visual inspection of rail tracks with a frequency of once or twice per week, depending on track speed. These manual inspections are currently performed by railroad personnel, either by walking on the tracks or by riding a hi-rail vehicle at very low speeds (F. Marino, 2007). However, such inspections are subjective and do not produce an auditable-visual record. In addition, railroads usually perform automated track inspections with specialized track geometry measurement vehicles at intervals of 30 days or less between inspections. These automated inspections can directly detect gage widening conditions. (R. Girshick, 2014).

Also Ultrasonic Rail-Inspection System (URS) is used to inspect the railway tracks. The result of the inspection is a series of images which represent a sort of cross-section of the rail. The images have to be interpreted in order to recognise images of possible defects. Currently, the interpretation is done partly using an expert system with a simple set of rules and the remaining images have to be analysed by a human operator.

To increase the length of the rail track that can be inspected per year and to reduce the workload on the operator it has been decided to improve the automatic interpretation subsystem. Of the many requirements that the new system should fulfil probably the most important is that it should be easily adaptable to the planned increase in the number of ultrasonic sensors. After analysis of the problem, case-based reasoning came up as the most promising methodology. (Jarmulak, 1996)

Figure 6 Different ultrasonic sensors used. (Hirotronix Sensors and Solutions INC.)

2.2.2 Actual repairing process.

The rails may be manufactured with internal defects or, as a result of wear-and-tear, develop defects. Such defects include, but are not limited to, inclusions, pits, rust, welds, batter, and engine burns. Such defects need to be repaired in order to safely operate the railroad. There are two common methods of railroad repair the mite welds and flash-butt welding. Rails repaired by flash butt welding are typically stronger and higher in quality than those repaired by a thermite weld. Additionally, rails may be temporarily repaired through the use of Joint Bar Splices.

When repairing a rail with a thermite weld, a portion of the rail localized around the defect is removed. The thermite material is then poured in a mould. AS the thermite material cures, it forms a plug which bonds to, and is contiguous with, the rail being repaired (Australia Patent No. AU9657001A, 2001). The area of the rail having the thermite weld material is not as Strong and is not of the same quality as a normal rail. AS Such, the thermite weld may require Successive repairs in order to maintain the railroad rail in a Safe condition. This method also requires the repair crew to transport the repair materials to the repair site.

Flash-butt welding is accomplished by bringing two ends of rail Segments together and passing a current through the interface. AS the current passes through the interface the rail becomes heated and malleable to the point where the two rail ends are forged together to provide a weld. When repairing railroad rail using flash-butt welding, a portion of the rail, typically five feet to nineteen feet, on both sides of the defect is removed. A new rail Segment is then placed in the gap left by the removed rail. The two ends of the replacement Segment are then flash-butt welded to the original rail. The rail Segment is then shaped to match the existing rail. This repair method results in the removal of a considerable length of rail and requires two flash-butt welds in order to complete the repair. This process is time consuming and requires the repair crew to transport repair materials is addition to the repair equipment. (Tachieva, 2010)

Joint Bar Splices are, essentially, a reinforcing clamp applied to the rail adjacent to the repair. A Joint Bar Splice is used when there is not enough time to perform a complete repair or when other repair materials are not available. A Joint Bar Splice, by government regulation, is a temporary repair and must be replaced in about 90 days. The Joint Bar Splice reduces the operational limit of the rail in the repair aca.

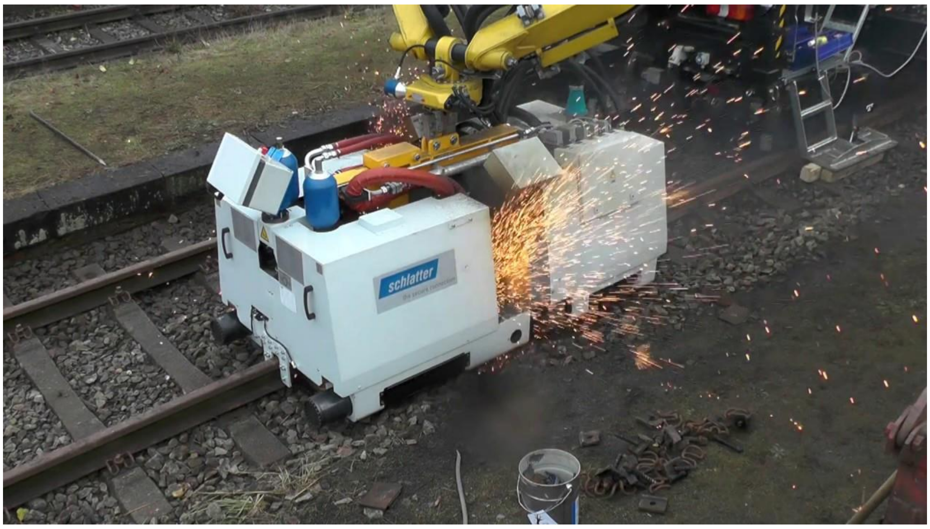

Figure 7 AMS200 Rail Welding Machine Supra Roadflex: Track Repair

Regardless of the repair method used, there is a need to track the Neutral Rail Temperature (“NRT). The NRT is based on the temperature of the rail when the rail is installed. The rails are structured to contract and expand in response to environmental temperature changes. The amount of expansion and contraction is determined by the NRT. When a repair is made, the NRT of the rail is altered.

2.3 Repairing process for rails

2.3.1 Proposed new technology

The technology proposed for this project is to incorporate a complete system that involves inspection and repairing both working in synchrony to achieve a complete task on the rail.

The principle point of start is the vehicle that can be capable of transporting all the subsystems that will work together. This vehicle has to be autonomous, which means that the location has to be reached without any human intervention. There are different ways to approach this:

- Planning a route through GPS.
- Giving measurements to the track.

Both methods require a certain precision as the fault location has to be accurate to be repaired.

In terms of inspection of the rail there are plenty of different devices to work with, but the decision was to make it visual. Recent advances in CMOS imaging technology, have resulted in commercial-grade line-scan cameras that are capable of capturing images at resolutions of up to 4,096x2 and line rates of up to 140 kHz. At the same time, high-intensity LED-based illuminators with life expectancies in the range of 50,000 hours are commercially available. (J. G. Allen, 2004).

The inspection system will have high-quality images that with an imaging processing protocol can detect the fault type and its operating mode (Y. Hu, 2009).

The repairing process is made by a robotic arm that is capable of, depending on the end effector, make any task previously set by the user. The repairs are autonomous and precise.

In order to simulate the complete system software in the loop was developed, the software is capable of simulating the vehicle and the robot motion, and an HMI that will display position, tasks, arm information and operations. The simulation demonstrates all the features of the complete system that has been proposed by In2Smart program. Figure 3 is a screenshot of the simulation of the vehicle in real-time and figure 4 is a picture of the human interface screen.

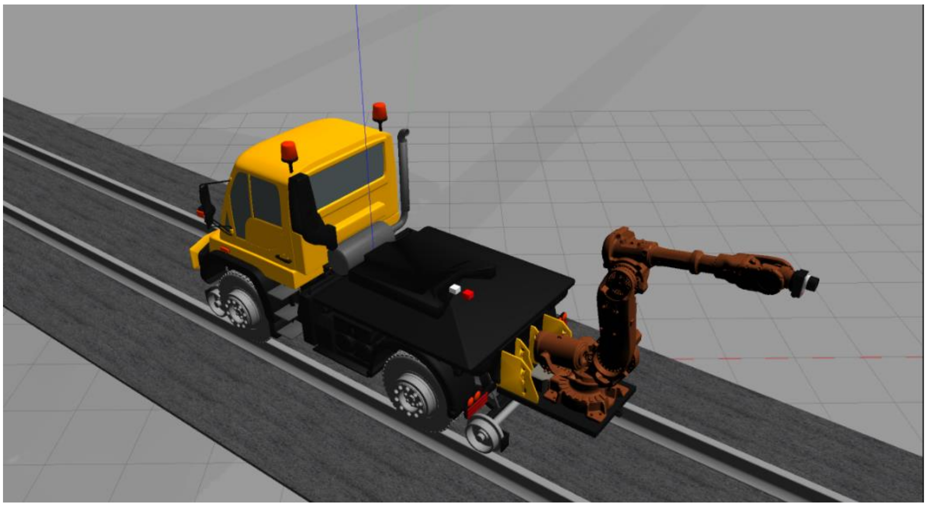

Figure 8 TSC Simulation of the vehicle (RIRS software)

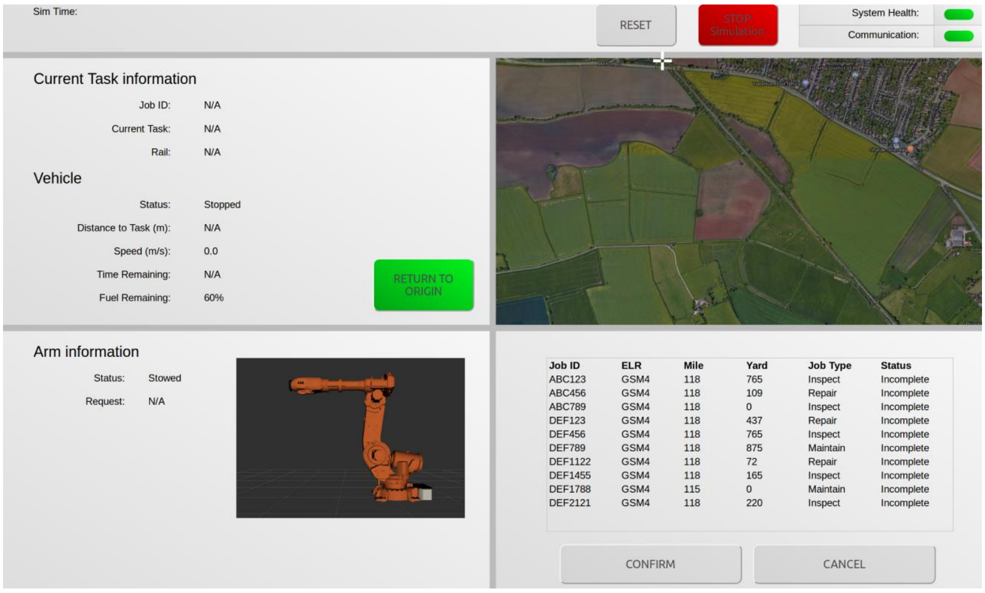

Figure 9 TSC HMI screen shoot (RIRS software)

On the other hand, a physical demonstrator was developed by Cranfield University, this has the objective to bring the system into a more tangible environment displaying this demonstrator in conferences, where the public can visualize more perceptibly the features of the system and show that the system can be implemented.

2.4 Scalability of the system

Design scalability is a technique used in routine design and manufacturing to adapt existing design knowledge to varying requirements. Guidelines exist for design scalability for subtractive manufacturing but there is much less support for components produced through an additive manufacturing process. (Górski, 2013)

Additive Manufacturing (AM) refers to a manufacturing technology that produces physical parts from a 3-dimensional computer-aided design (CAD) models to produce workpieces by depositing materials in successive layers without the need of any conventional tooling. (Bergman, 2009)

Taking things into consideration is complicated to deliver scalability based on the result of the repairs. The main objective of the scalability of the system is to divide it into different sub-systems that can be tested and scale into the actual industry, with the existing technology and find the key factor to implement this system.

The sub-systems will be considered after the requirements given by National Railway, and are divided into:

- Motion
    - Obstacle avoidance
    - Location
    - Correct positioning
    - Speed control
- Inspection
    - Fault search
    - Image processing
    - Classification of faults
- Repair
    - Type of repair
    - Positioning
    - Stability

These are the three main sub-systems which also have internal categories that link one and other. Each one has to be available to scale its components into industrial size.

2.5 Technology Readiness Levels

Technology Readiness Levels were originally conceived at NASA in 1974 and formally defined in 1989. The original definition included seven levels, but in the 1990s NASA adopted the current nine-level scale that subsequently gained widespread acceptance.

Technology readiness levels (TRLs) are a method for estimating the maturity of technologies during the acquisition phase of a program, developed at NASA during the 1970s. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology (Héder, 2017). A technology's TRL is determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRLs are based on a scale from 1 to 9 with

9 being the most mature technology. The current nine-point NASA scale is: (NASA, 2000)

- TRL 1 - Basic principles observed and reported
- TRL 2 - Technology concept and/or application formulated
- TRL 3 - Analytical and experimental critical function and/or characteristic proof-of-concept
- TRL 4 - Component and/or breadboard validation in a laboratory environment
- TRL 5 - Component and/or breadboard validation in a relevant environment
- TRL 6 - System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- TRL 7 - System prototype demonstration in a space environment
- TRL 8 - Actual system completed and "flight qualified" through test and demonstration (ground or space)
- TRL 9 - Actual system "flight-proven" through successful mission operations

The primary purpose of using technology readiness levels is to help management in making decisions concerning the development and transitioning of technology. It should be viewed as one of several tools that are needed to manage the progress of research and development activity within an organization.

Among the advantages of TRLs: (Deutsch, Meneghini, Mermut, & Lefort., 2012)

- Provides a common understanding of technology status
- Risk management
- Used to make decisions concerning technology funding
- Used to make decisions concerning the transition of technology

Some of the characteristics of TRLs that limit their utility:

- Readiness does not necessarily fit with appropriateness or technology maturity

- A mature product may possess a greater or lesser degree of readiness for use in a particular system context than one of lower maturity
- Numerous factors must be considered, including the relevance of the products' operational environment to the system at hand, as well as the product-system architectural mismatch
- Current TRL models tend to disregard negative and obsolescence factors. There have been suggestions made for incorporating such factors into assessments.

For complex technologies that incorporate various development stages, a more detailed scheme called the Technology Readiness Pathway Matrix has been developed going from basic units to applications in society. This tool aims to show that a readiness level of technology is based on a less linear process but a more complex pathway through its application in society.

2.6 Methodology

2.6.1 V-Model

The project scope requires a research methodology that allows iterations of a tested prototype and realizes several modifications while the project is ongoing. The development cycle for projects usually starts with User needs, which are then translated into a feasible set of system requirements. The system requirements are progressively decomposed into baselines for segments, elements, and more until the lowest level of detail, hardware parts or software units, are specified. The physical parts, assemblies, or software units are then integrated into successively higher assemblies, until the integration process is complete as evidenced by a functioning, validated system. One of the methodologies that provide the opportunity to review and iterate a result is the V-model method.

The V-model is a graphical representation of a systems development lifecycle. It is used to produce rigorous development lifecycle models and project management, models. The V-model summarizes the main steps to be taken in conjunction with the corresponding deliverables within the computerized system validation framework, or project life cycle development. It describes the activities to be performed and the results that have to be produced during product development. (Forsberg & Mooz, 1998)

The left side of the "V" represents the decomposition of requirements and the creation of system specifications. The right side of the "V" represents the integration of parts and their validation. However, requirements need to be validated first against the higher-level requirements or user needs. Furthermore, there is also something as validation of system models. This can partially be done on the left side also. To claim that validation only occurs at the right side may not be correct. The easiest way is to say that verification is always against the requirements, technical terms, and validation always against the real world or the user needs. (Horno, 1996)

It is important to clarify what is validation and verification and these two will give the corresponding transparency for relying on the RIRS system. (IEEE, 2012)

- "Validation. The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers. Contrast with verification."
- "Verification. The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. Contrast with validation."

The V-model guides the planning and realization of projects. The following objectives are intended to be achieved by a project execution:

- Minimization of project risks: The V-model improves project transparency and project control by specifying standardized approaches and describing the corresponding results and responsible roles. It permits early recognition of planning deviations and risks and improves process management, thus reducing the project risk.
- Improvement and guarantee of quality: As a standardized process model, the V-Model ensures that the results to be provided are complete and have the desired quality. Defined interim results can be checked at an early stage. Uniform product contents will improve readability, understandability and verifiability.
- Reduction of total cost over the entire project and system life cycle: The effort for the development, production, operation and maintenance of a system can be calculated, estimated and controlled transparently by applying a standardized process model. The results obtained are uniform and easily retraced. This reduces the acquirer's dependency on the supplier and the effort for subsequent activities and projects.

- Improvement of communication between all stakeholders: The standardized and uniform description of all relevant elements and terms is the basis for the mutual understanding between all stakeholders. Thus, the frictional loss between user, acquirer, supplier and developer is reduced.

In systems engineering, the V-model is widely used to structure ideas and concepts of systems development. It graphically shows connections between development, integration, verification and validation. In the V-shaped diagram, the level of detail increases from top to bottom. (Starr, 2019)

The verification stream a defined method should be considered and the process will be dictated by the following four elements:

- Inspection
- Modeling and simulation
- Demonstration
- Test

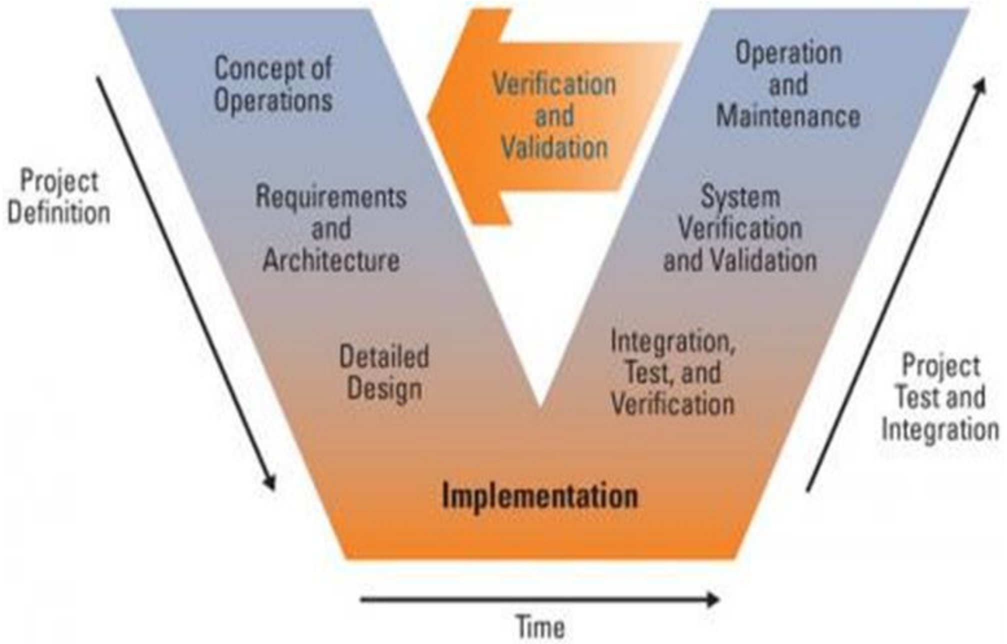

Figure 10 Systems Engineering V-model. Source: Clark, IEEE SysCon 2009

For this project the following outcomes of verification are requested to continue with the V-model procedure:

- Constraints of verification that influence the requirements, architecture, or design are identified;
- Any enabling systems or services needed for verification are available;
- The system or system element is verified;
- Data providing information for corrective actions is reported;

- Objective evidence that the realized system fulfills the requirements, architecture, and design is provided;
- Verification results and anomalies are identified;
- Traceability of the verified system elements is established.

The incorporation of the Vmodel helps in the scalability of the system as with its cyclic structure allows the detection of the challenges and the benefits of the system. Also each iteration will be performed taking in consideration the TRL.

2.6.2 Case of study

As the organization of this research requires several iterations for the development of the RIRS it was clear that using the first physical demonstrator and the software in the loop as a case of study was the way to continue the research, as these two will be verified and valididated by the tests performed.

In this type of research, a case study is a study method involving an up-close, in-depth, and detailed examination of a particular case, for the benefit of this paper the case will be the physical demonstrator. A case study should be defined as a "research strategy", an empirical inquiry that investigates a phenomenon within its real-life context. The resulting body of 'case study research' has long had a prominent place in many disciplines and professions. (Yin, 2013)

An average, or typical case, is often not the richest in the information. In clarifying lines of history and causation it is more useful to select subjects that offer an interesting, unusual or particularly revealing set of circumstances. A case selection that is based on representativeness will seldom be able to produce these kinds of insights. When selecting a case for a case study, researchers will, therefore, use information-oriented sampling, as opposed to random sampling. Outlier cases that reveal more information than the potentially representative case, as seen in cases selected for more qualitative safety scientific analyses of accidents. A case may be chosen because of the inherent interest of the case or the circumstances surrounding it. Alternatively, it may be chosen because of researchers' in-depth local knowledge; where researchers have this local knowledge they are in a position to enter and discover, thereby offering reasoned lines of explanation based on this rich knowledge of setting and circumstances.

Summering there are three types of cases may thus be distinguished for selection:

- Key cases.
- Outlier cases
- Local knowledge cases

For this thesis, the combination of a key case with the local knowledge that developing the physical demonstrator will give makes a reasonable method to follow and to give an idea of how to continue with the research.

3 Physical Demonstrator

The development of a physical demonstrator, to make evident that the Command and Control System with the RIRS is functional, was the responsibility of Cranfield University. The RIRS physical demonstrator will accomplish the requirements of the major stakeholder, Network Rail.

The robotic inspection and repair demonstrator should comprise of:

- A miniature railway carriage.
- Fitted instrumentation capable of searching for and finding a simple simulated "fault".
- A miniature robot fitted with an end-effector capable of "repairing" the fault.
- A monitor to display the key steps through which the controller is progressing.

The concept of the demonstrator the following:

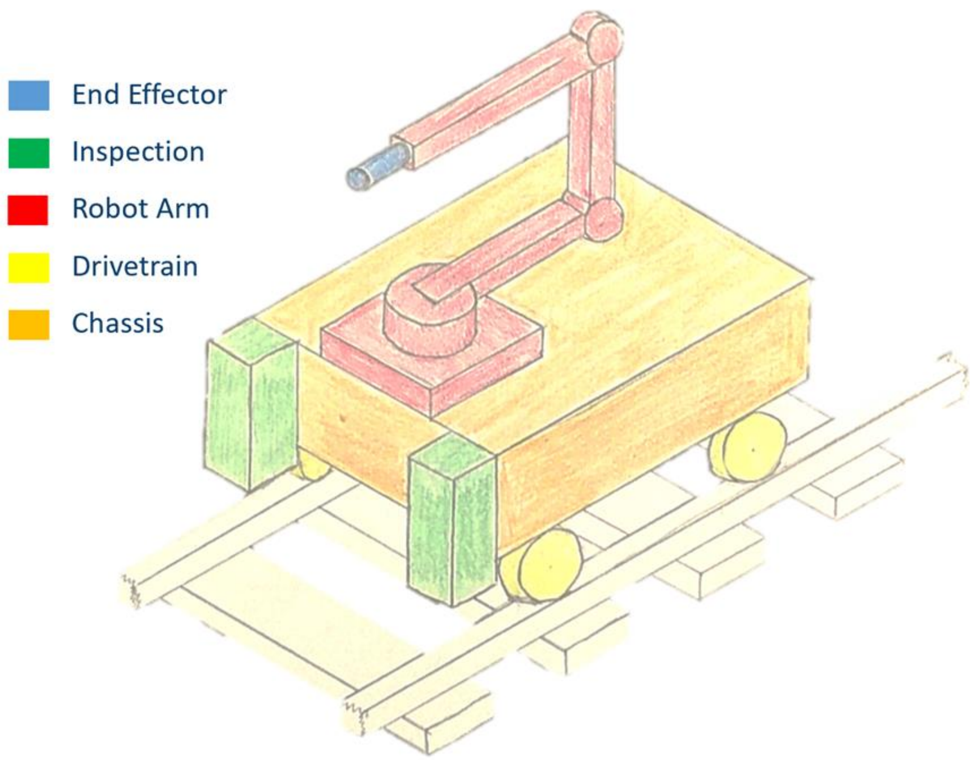

Figure 11: RIRS Concept Drawing

The final result was a 1:11 scale vehicle with a robotic arm mounted on real scaled rails as shown in the Figure 12:

Figure 12: Physical Demonstrator Picture

The physical demonstrator has the ability to autonomous sense the defect, detect it, after it will retract to give the robotic arm enough workspace and then repair the fault.

The sensing method to find a fault is via cameras and the repairing process is additive manufacturing by 3D printing.

The requirements for this demonstrator were stablished by In2Smart and Shift2Rail. Network Rail and Cranfield design the initial concept and adquire the components that complies with the concept.

3.1 Scope of the physical demonstrator

In consultation with Network Rail, the following requirements were defined. First, considering the availability of the standard components and the size of robots currently available in the market, we have decided to use the 5-inch gauge model rail for the physical demonstrator. This corresponds to a scale of 1:11.3 against the real rail structure and this proportion to the real standard dimensions was used throughout the study.

Second, the scope of the maintenance activities was defined. As depicted in Figure 13. Three areas can be identified for asset maintenance activities.

However, due to the time constraint, we have chosen Area A, among others, rail defects, as the initial target of the study.

- Area A: Beneath the carriage: e.g., rails, sleepers, ground, (part of) bridge structure
- Area B: Side area: e.g., tunnels walls, (part of) bridge structure
- Area C: Above the carriage: e.g., overhead line, tunnel ceiling

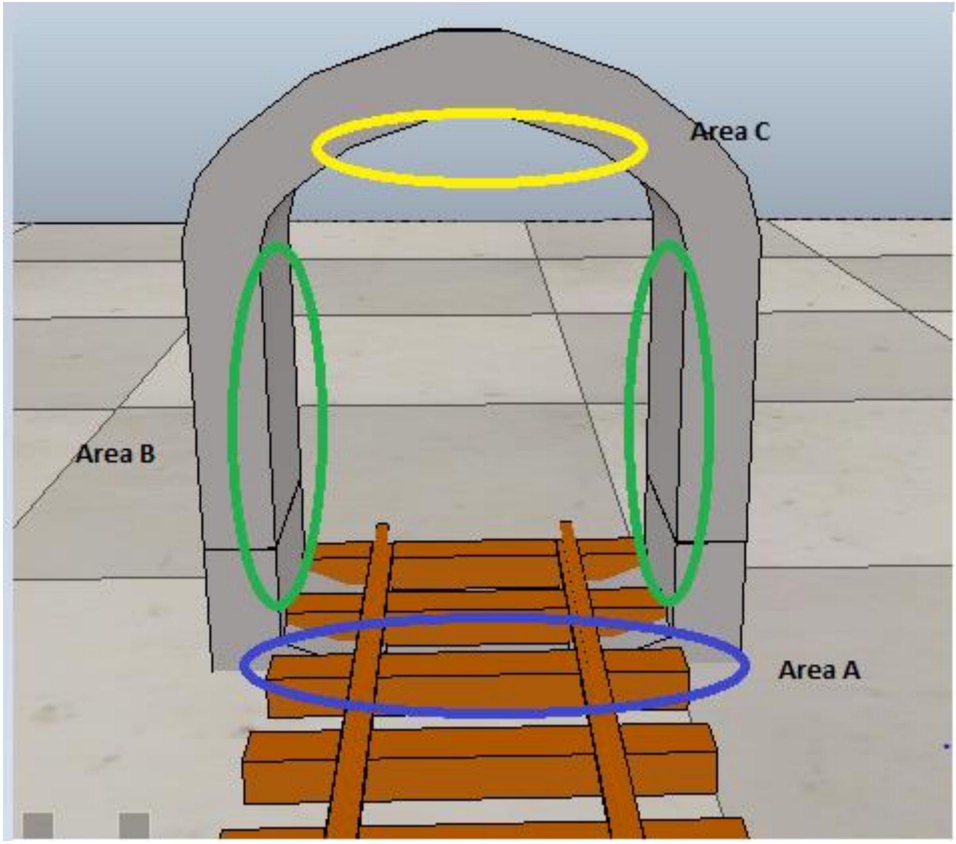

Figure 13: Servicing Areas

Following this scoping, the requirements were identified and analyzed in collaboration with Network Rail and are displayed in the following chapters.

3.2 Aim and requirements of the demonstrator

The proposal for having a physical demonstrator for an agnostic vehicle with a Command and Control System incorporated was accepted as part of the In2Smart initiative. The In2Smart initiative was divided into different Work Packages (WP) to ensure the complete functionality of the new technologies that will be incorporated into the industry. One of the deliveries of the WP10 is a physical demonstrator for the system, capable to perform the CCS and the RIRS activities.

The aim is to have a testing platform to verify that the technology is functional and can solve the rail industry problems.

The requirements for this physical demonstrator were set by Network Rail, one of the major stakeholders of the project. The requirements were discussed with Cranfield and several compromises have been made as the timeframe to deliver the demonstrator was short, from the complete list of requirements a compact set of them was agreed and decided that the demonstrator will accomplish, 24 main requirements, which are a key factor to solve the industry problems, were defined and are shown in Table 1: Physical Demonstrator Main Requirements. The complete table of requirements from Network Rail can be found in 7Appendix A.

Table 1: Physical Demonstrator Main Requirements

ELEMENT N.	ELEMENT	PHYSICAL LAB-BASED DEMONSTRATOR COMMENTS	REQ.
	Prototype Demonstration Process		
1	RIRS-CD replenishment and module check	As there is only one task, no module check is required. PLA filament will be supplied during the setup of the demonstration.	-

2	Predefined worklist	No worklist, due to singular use case for inspection and repair	-
3	Motion plan	Motion plan not necessary because there is no indication of the path to follow, but the streaming images will be displayed on the OI	02.2.1 04.3.2
4	The operator confirms that the right defect location has been reached		02.2.4 05.2.2
5	Defect inspection technology	Cameras and sensors	02.4.2 04.3.1
6	Definition of defect severity	One type of defect	-
7	Operator's approval for starting the repair task		02.2.3 05.2.1
8	Reports to the RDMS	Notifies the operator when data would be sent to RDMS. It does not send real data	05.3

9	Repair operations	3D printed element filling the gap	02.3.2 05.1.2
10	STOP option of the repair process	STOP option always available for freezing the robotic arm. When the robotic arm is stopped, a reset function can be activated to make the arm come back to the original position. Other STOP option available during the 3D printing for blocking the filling process	02.2.2 05.2.6
11	Quality check of the repair	Streaming image displaying the 3D printing process. If necessary the operator can stop the system.	02.2.1 05.2.4
12	Data exchange with Ellipse	Does not exchange data with Ellipse	-
13	Audience participation in the demonstration		-

14	Operator co-located with the prototype during the demonstration		-
15	Interaction between the prototype and the operator interface		02.2.4 05.2
Other Project's elements			
16	Benefits demonstrated: risk reduction for inspection and repair, data providing and stakeholders engagement		-
17	Disadvantages highlighted: staff retraining, reduced flexibility for poor condition rail inspection, the area required for system storage		-
18	Objective: development and test activities in a representative		02.1.2 03 05

	environment, stakeholders engagement in the solution proposed		
19	System's components	- Tracks - Bogie - The robotic arm (end effector with 3D printer head and camera) - Inspection cameras attached to the bogie - Operator interface - Power system	02.1 02.3 04
20	Area of inspection and repair	- Track inspection and repair	02.4.2 04.3.1
21	Simulation	The simulation used as: - System and concept design testing - Interaction with OI - Demonstrator control logic - Demonstration process testing	04 05 06
22	Hazard identification and classification, risk analysis	Hazards associated with a demonstrator to be documented	03.1
23	System requirements definition		01 02

			03 04 05 06
24	Functional and network model, logical interfaces	UML mapping of the different components of the system and their communication developed in another Cranfield student thesis	-

3.3 Purpose of the demonstrator

As the technology is new to the industry, there is no other similar concept in operation or any research made in this area. Having a physical demonstrator will give the project a better understanding of what an RIRS is capable to do in a real environment and will contribute to the analysis of the implementation of these technologies.

The physical demonstrator allows testing and also determines the scope of the scalability, giving a complete list of possible challenges and giving a different view of the current capabilities of the system.

Taking into consideration that finding the information to develop the concept RIRS represents a high risk and a challenge, the physical demonstrator will be the reference for a new generation of technologies with similar scope.

3.4 Development of the physical demonstrator

3.4.1 Systems design

As the first step in designing the physical demonstrator, its systems design was conducted. The first steps were to map the different subsystems. This was done by identifying each of the subsystems and defining their functions concerning the overall system.

The identified subsystems encompassing in the robotic demonstrator and Table 1 are functional descriptions of these subsystems. After embodying these functions with concrete mechanisms and determined their configurations and parameters (e.g., the number of degrees of freedom for the robotic arm), the design of the system of the demonstrator was completed.

Table 2: Subsystem Functional Description

Subsystem	**Function**
End Effector	Will deposit material to fix a defect.
Robot Arm	Will be mounted on the chassis and guide the end effector to fix the defect.
Chassis	Will hold all the subsystems together.
Inspection	Will analyze the rail and notify the control system whether the defect is on the right or left rail and its location.
Drivetrain	Will move the demonstrator when searching for a rail defect and stop the demonstrator in the correct position when it has found one.
Power Storage	Will provide the power to the robotic demonstrator.
Control System	Will control the robotic demonstrator

The robotic system is composed of a robotic arm located on a bogie moving on a track segment. As a way to agile manufacturing, a robot with a pre-installed 3D printer head was selected (Dobot Magician, https://www.dobot.cc). The robotic arm has three degrees of freedom, and its end effector is equipped with a 3D printer head. The system is equipped with two Pixy cameras, which are used for the inspection activities through color recognition. The chassis is also used to carry other essential elements for the system functioning, i.e., 3D printer filament, processors, and batteries.

3.4.2 Vehicle hardware description

The vehicle chassis was modified from a “Jupiter” kit supplied by Dorrington Technischen Räritäten. It is approximately 100cm long x 50cm high x 31cm wide. A vehicle body has been added (see Figure 14). The rear of the vehicle is modified to provide a loading bay, where some of the electronics and the robot are fixed. The rear chassis and buffer beam is kept clear to retain a clear path for the robot. Figure 14 also shows a traction motor and axle assembly. Four lengths of a track of length 1.25m allow a run of 5m.

Figure 14: Physical Demonstrator Mobile Unit

3.4.3 Vehicle control

The high-level control, illustrated in Figure 15, uses an Arduino controller programmed to run the following sequence. Its embodiment is shown in Figure 14.

Start

    [MESSAGE] Welcome

1 Origin setting

    [MESSAGE] Starting to move to origin

Reverse to origin slowly

Detect origin hardware switch (switch on the vehicle; hardware stop)

Set zero

    [MESSAGE] Found origin

2 Wait

    [MESSAGE] Press button to start

    Press green button to start

3 Fault detection cycle

    [MESSAGE] searching…

Move forward fast

    Detect fault from sensor – record absolute location

    Detect rail side – left or right

    (overshoots)

    [MESSAGE] found fault

    Reverse slowly to fault position

4 Command to robot

[MESSAGE] starting repair

Robot cycle start and finish – left or right

[MESSAGE] repair finished

5 Return to origin – fast then slow

[MESSAGE] returning home

6 Go back to 2

[MESSAGE] system ready

Stop

[MESSAGE]

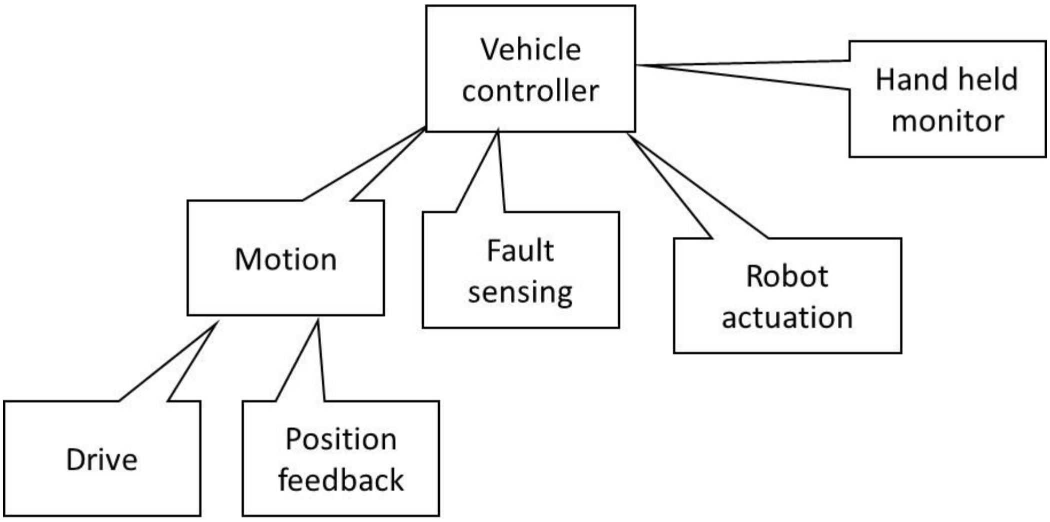

Figure 15: Control Sequence

3.4.4 Drive system

The motor bogie has been modified to install an encoder to determine the position. One electric motor drives the vehicle. A second motor has been removed, to limit the current drawn. The drive system is shown in overview in Figure 16, and the controller embodiment is shown in Figure 14.

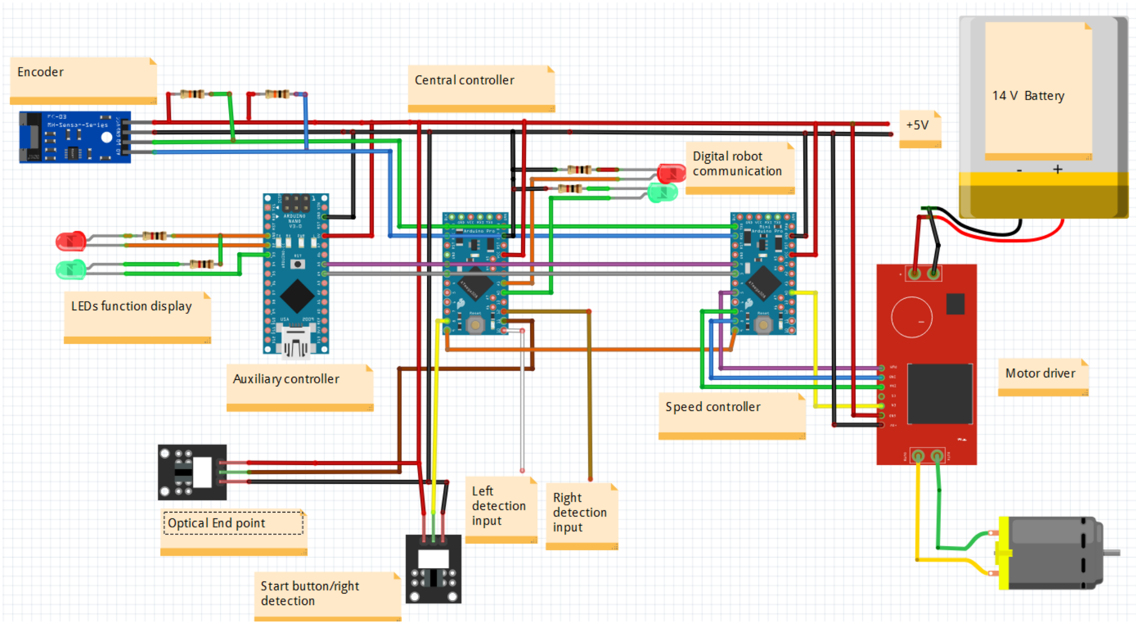

Figure 16: Electrical Conexion for the Controller

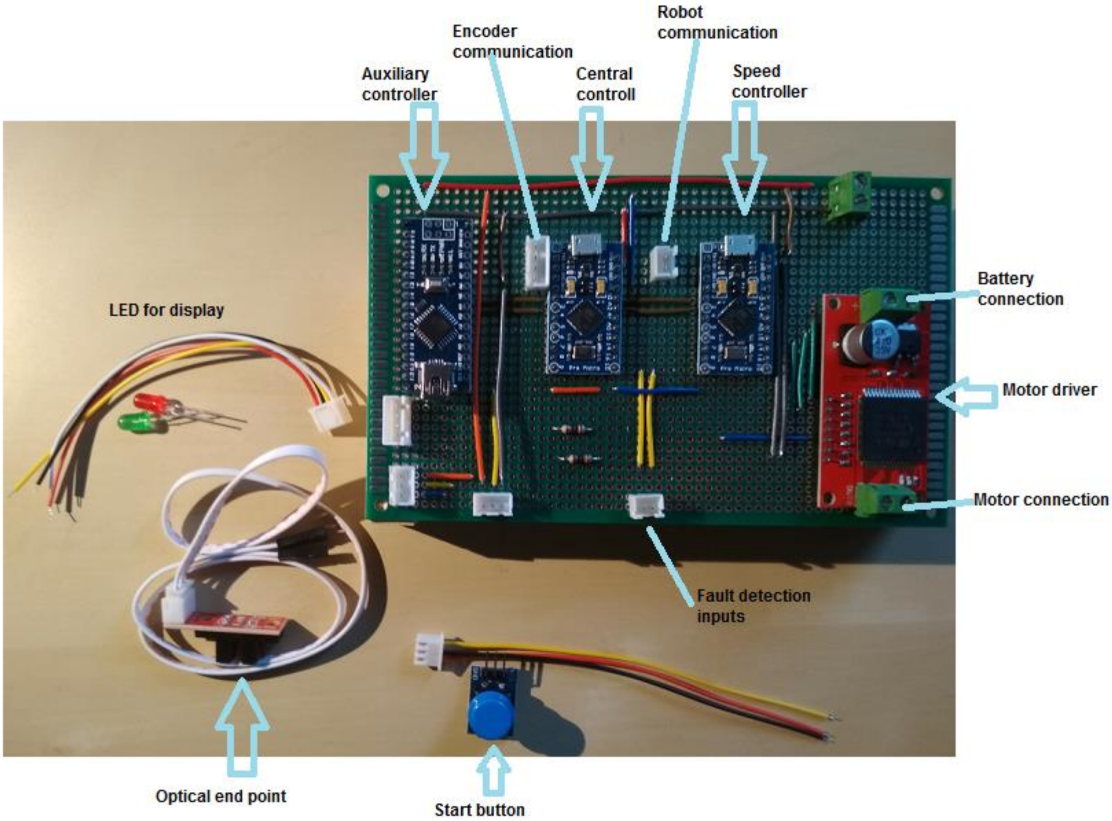

Figure 17: Main Board I/O

3.4.5 Fault detection

The sensing system is based on Pixycam camera boards, modified to remove motion control, and fixed under the robot with 3D printed brackets. There are two cameras, one for each rail. The cameras are programmed to detect the color of the simulated faults. LED lighting ensures robust detection. Each camera communicates through an Arduino with the main system controller.

The efficiency of the fault recognition is below the 80% as the detection will depend on the light and the colour detection, but as this is a demonstrative concept is completely acceptable for the development of the control system.

3.4.6 Electric and electronics

The power supply is drawn from a large 14.8V lithium-ion battery. The battery supplies:

- Traction at full voltage; motor power is controlled by an electronic speed controller (ESC) or “shield” driven by the Arduino;
- The robot and 3D print head at 12V; current at up to 7A is supplied for the printer head heater, which is switched by the robot;
- Control and sensing electronics at 5V.

Voltage conversion is made through proprietary DC-DC converters. The battery is protected by circuit breakers and an emergency stop button is fitted to cut the entire power system. The circuit diagram schematic for the power supply is shown in Figure 18.

The emergency stop button cuts the power when it is depressed. It must be pulled up to release.

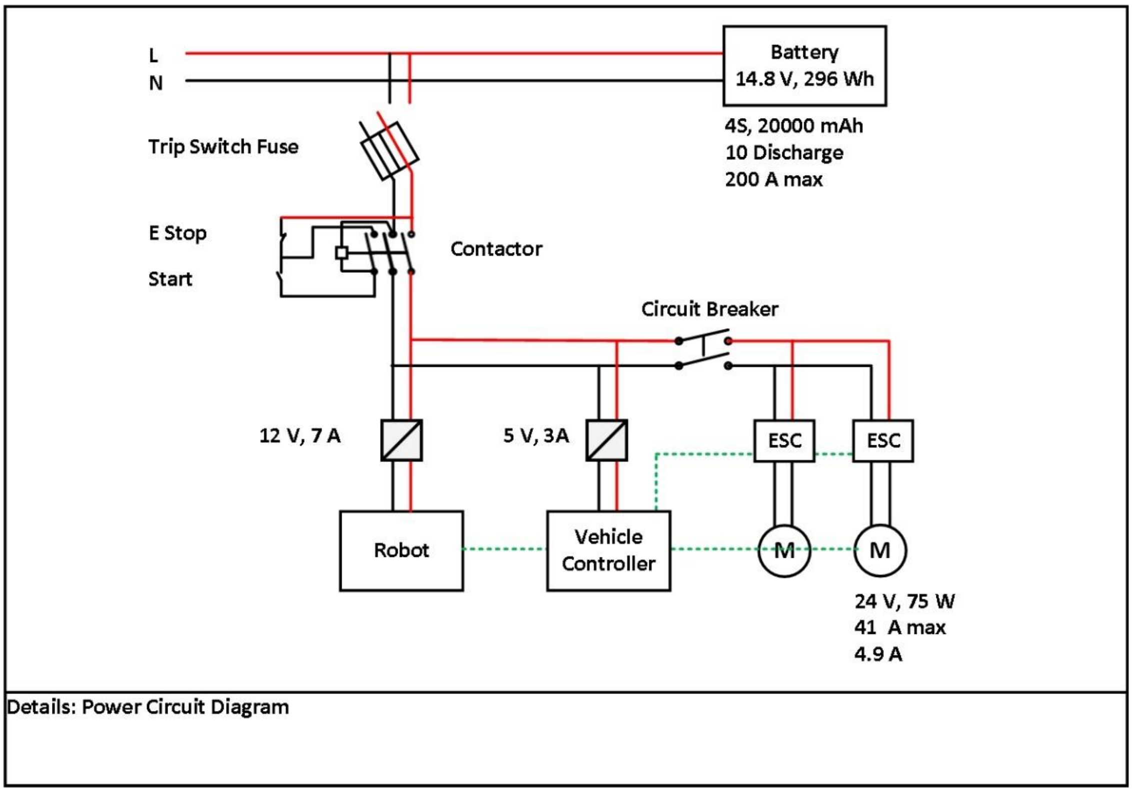

Figure 18: PixiCam Connexion

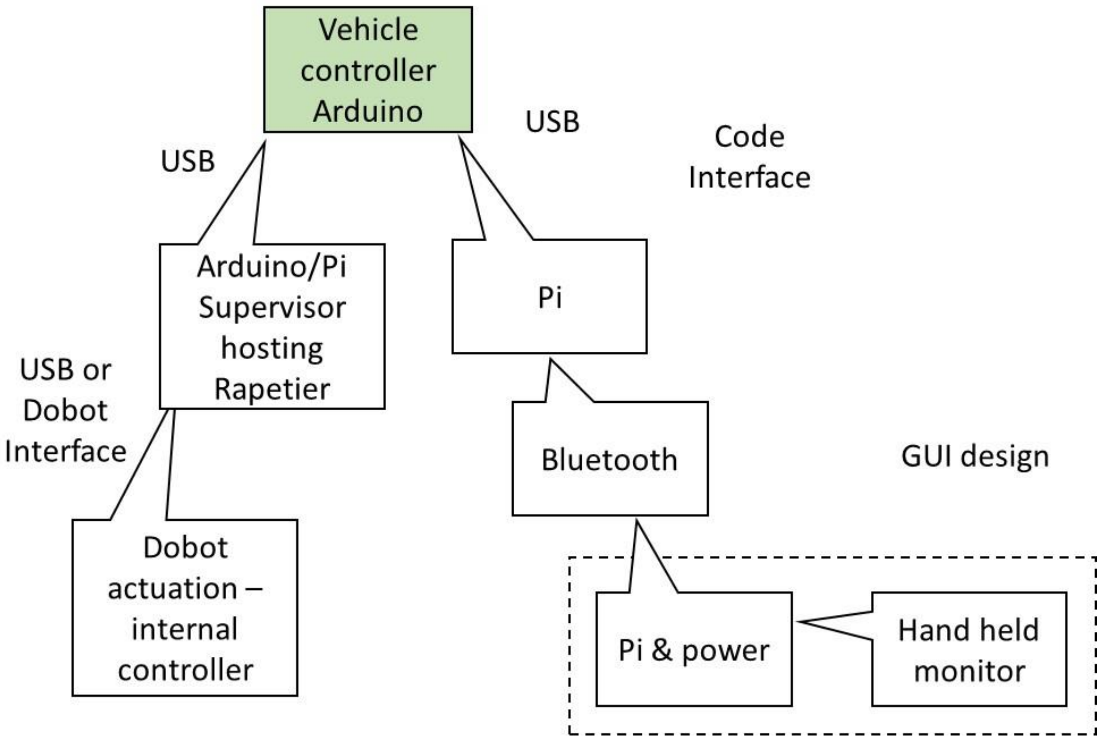

Figure 19: Main Control Diagram

3.4.7 Robot and rail repair

The Dobot robot is programmed to respond to the vehicle controller's command to make a 3D print simulated repair on either rail. It draws subroutines from a virtual server hosted locally and follows scan codes to apply layers of polymer print on the target. The robot also performs the switching of the 3D print head.

3.4.8 Hand-held device

A hand-held monitor is provided to show the steps in the vehicle's progress. All the steps in section **Error! Reference source not found.** are transmitted as text codes by wireless connection. The monitor displays what it receives, and does not transmit messages to the vehicle.

3.4.9 Position control

To achieve a robust positioning of the robot, several adaptations were applied to the robot. This upgrades to the motion of the train and the robotic arm allows a smooth approach to the fault and accurate location of the 3D printing process.

3.4.9.1 Encoder

The robot is capable of detecting a fault in a specific location of the track using the camera detection system, but to achieve a better position and give enough space to the robotic arm to operate, a precise location of the train was implemented using an encoder.

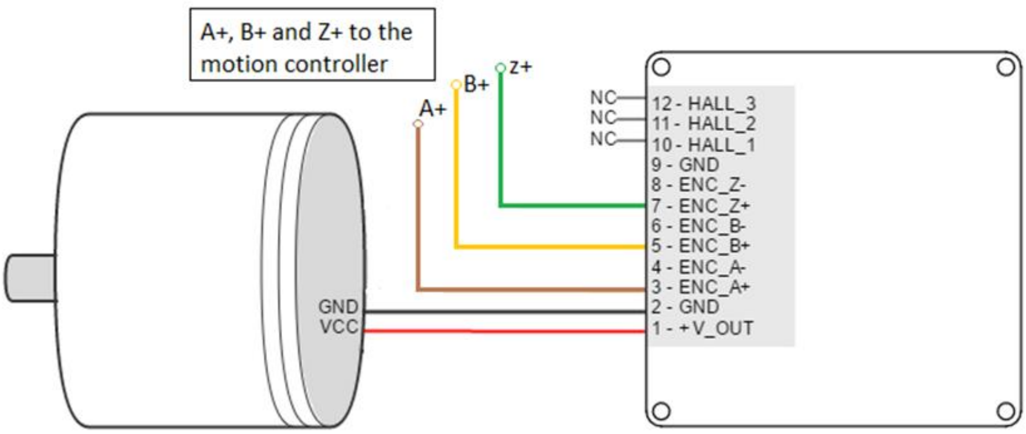

Figure 20: Encoder Connexion

The encoder provides feedback converting motion to an electrical signal that can be read by the controller. This signal can be used to determine position. Using a tag, that is located in the origin (home position) the value of the encoder resets to 0 from which it starts counting and giving a measure.112 readings of the encoder are equal to 1cm.

3.4.9.2 Braking system

The motor generates a considerable amount of torque to move the train. The torque and the low friction between the rail and the train wheels produce inertia that creates an error in position the robot arm for the intended repair. To solve this issue a mechanical brake was added to one of the wheels, creating more friction that will stop the train from slipping from the stopping location.

The break was designed specifically to the measurements of the train, the parts were 3D printed, assembled and installed on the wheels of the train.

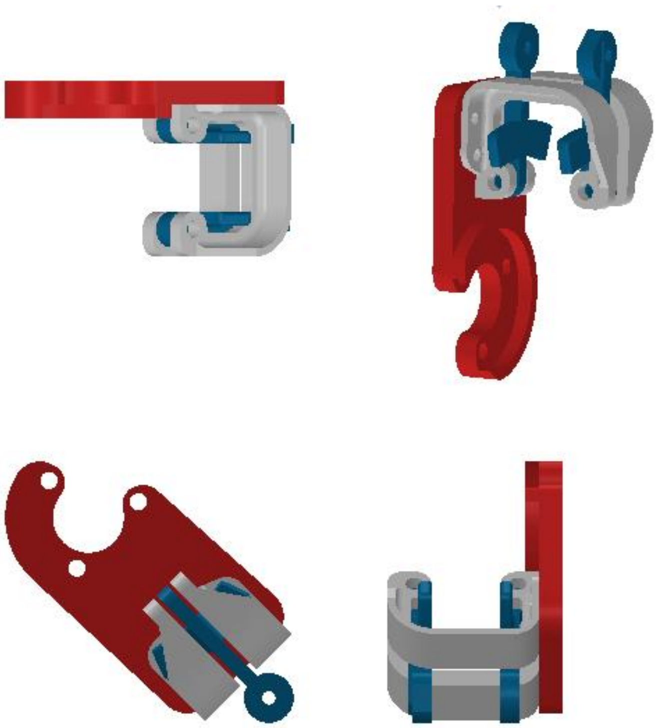

Figure 21: Breaks CAD Models

3.4.10 Sub-system interface

The demonstrator was divided into several sub-systems working independently:

- Motion control
- Position control
- Fault detection camera system
- Robotic arm control
- 3D printing
- LED indicators
- Handheld device

These sub-systems have to communicate in real-time, making the data transferring a key factor for the autonomy performance of the robot. The main controller that receives all the data and executes the required actions has to be robust and capable to process the information delivering specific orders to each of the sub-systems.

Arduino was selected as a controller for motion, fault detection, positioning and light indicators. 5 Arduinos are working separately on different tasks, each one communicates using I2C protocol (Inter-integrated Circuit).

The Inter-integrated Circuit (I2C) Protocol is a protocol intended to allow multiple "slave" digital integrated circuits to communicate with one or more "master".

The Dobot, used as the robotic arm, has the server that runs the commands to move it and executes the 3D printing process, to communicate with the server a Raspberry Pi was used. Considering that the Arduino and Raspberry Pi have different processing times, the I2C protocol was not an option, but a digital I/O communication was the solution.

The robot control has a python program that links the robot web server to the Raspberry Pi and uploads the G-code needed depending on the side of the rail that has to be repaired.

The handheld device reflects the process made by the main controller and shows the messages received. These messages can be found in section 3.2.4. The communication between the handheld device and the main controller is through the Raspberry that controls the robot arm movement, this communication is via

USB Serial. The display has a connection to the Raspberry through VCN communication that requires the IP from the host (Raspberry Pi) and it will display the messages sent by the Arduino. The schematic for the communication between controllers is displayed in Figure 22.

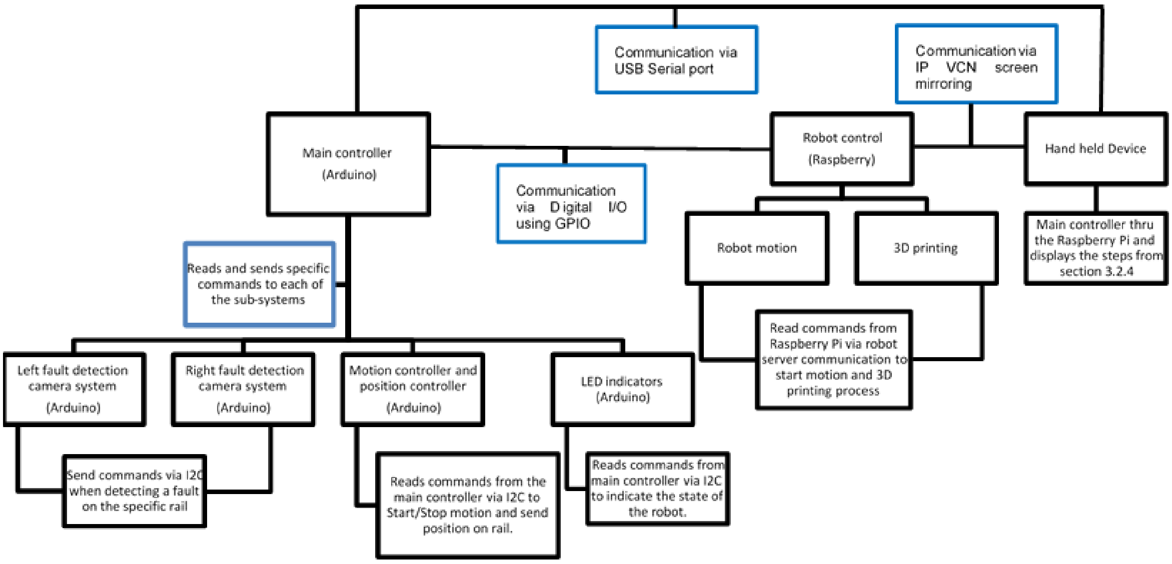

Figure 22: Main Controller Flow Chart

3.5 Final view of the physical demonstrator

A physical demonstrator for a railway inspection and repairing robot has been developed. The vehicle demonstrates the following:

- A realistic train system capable of simulating inspection and track repair, with an approximate 1/11 scale
- Autonomous fault search and detection on a railway using vision detection systems.
- Autonomous fault repair, using 3D printing capability of PLA filament on the railway.
- Communication with a remote user via a hand-held monitor that reflects the work executed by the robot.

- Vehicle-User communication using a remote hand-held monitor reporting robot task instructions.
- The demonstrator is suitable for exhibition environments.
- The demonstrator uses modular sub-systems enabling upgrades and modifications.

The following steps are to realize the V&V procedure and analyze the scalability of the TRL for this prototype.

4 Validation and Verification of the system

The validation and verification of the physical demonstrator aim to enable a series of development and test activities in a representative environment, which tackle identified areas of high risk to the program and demonstrate performance in realistic scenarios. Additional benefits are to be realized through being able to engage stakeholders with a meaningful representation of the production solution to facilitate new requirements and validate existing requirements

The RIRS demonstrator is proposed to provide both an increase in efficiency as well as in workforce safety.

4.1 Procedures

The V&V process will conduct functional testing of the RIRS physical demonstrator, the review of the stakeholders' requirements and the hardware demonstrator project scope, test over the main functionalities of the demonstrator and recommendations for upgrading the demonstrator.

To start with the V&V of the RIRS physical demonstrator, a complete review of the requirements was taken into consideration, the first requirements were the stakeholder. These requirements can be found in 7Appendix A of this report. Using the mentioned requirements and the ones presented from the TSC Software, guided the scope of the physical demonstrator V&V.

As a result of combining the most important requirements on the development of the system, a new table was created but with the necessities of the V&V of the physical demonstrator. 7Appendix A shows the requirements and the validation procedure made for the RIRS demonstrator.

After recording the requirements and separating them for the different subsystems of the demonstrator, 4 key factors were detected and put into consideration for verification tests:

1. Reliability of the system.
2. The autonomy of the system.
3. Control of the system.
4. Accuracy of the system.

These 4 factors were the most important to verify system viability and functionality. Each one of them has different requirements to accomplish to pass the verification process.

There were a total of 31 requirements to accomplish for the V&V of the physical demonstrator. All of them were analyzed and has been decided to do a minimum of 10 repetitions to verify the functionality of the demonstrator. For some subsystems like the power supply discharge, there was just 5 test to conclude its functionality.

To start with the reliability of the system an analysis of the mobility, repeatability, autonomy, duration and resistance were made. The test conduct on these phases established that the demonstrator is reliable and can be trusted to work during more than 1 hour of work without any charging of the main power supply.

The autonomy of the system was tested by considering the different phases that the demonstrator must achieve to have a complete repair of the system, the cycle that the RIRS must achieve is shown in Figure 23. The key features to achieve autonomy of the system were power supply, report status, fault detection, positioning and connectivity.

For the control of the system it was necessary to divide the demonstrator into the subsystems as all the subsystems should work independently and a master control should be work as a master. The motion of all the systems considered separately and also the connectivity for a handheld device was taken into consideration. The test was focused on the speed, fault detection, positioning and safety of the system.

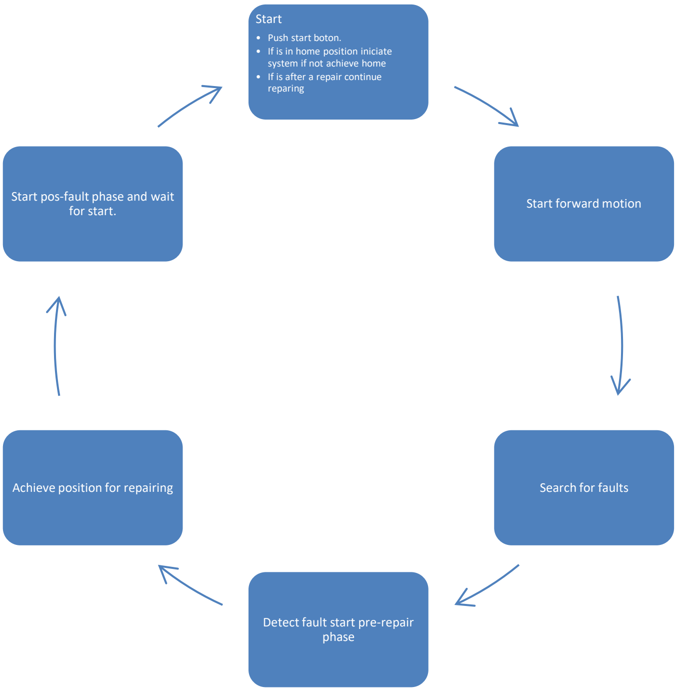

Figure 23: RIRS Cycle Performance

The last point was the most important and challenging as this will assure the functionality of the demonstrator and give the ability to execute the repair in the correct location, the accuracy of the system should be of high quality, this was tested and acquiring the most precise data possible. The test was focused on the X, Y and Z-axis plus the communication between subsystems and the robotic arm motion.

All the tests were realized in a controlled environment as shown in Figure 24.

Figure 24: Environment for the V&V Tests

Also a standardized system was used, the rail has to be leveled and have a minimum deviation of ±0.01 degrees. The track was leveled using a 1mm, 3mm 5mm and 6mm plastic elevators that helped with the right position of the rails. Figure 25 shows the level tools and its appliance on the rail.

Figure 25: Leveling Measurement for the Track

The faults were located at least with a 20cm separation between each other to have a good range of motion in the X-axis and allow the whole system to move smoothly. The importance of this was very important at the moment of calculating the accuracy of the demonstrator. The faults were simulated with red brackets, this will represent the finding of a fault on a certain location, this fault recognition will be simulating an alert for the main control system to react to this.

Two different types of brackets were used one of 5cm length and 3.5 cm width and the second one a square of 3cm per side. This variation in the size of the brackets was intended to demonstrate the capacity of the system to achieve great precision considering all the external factors.

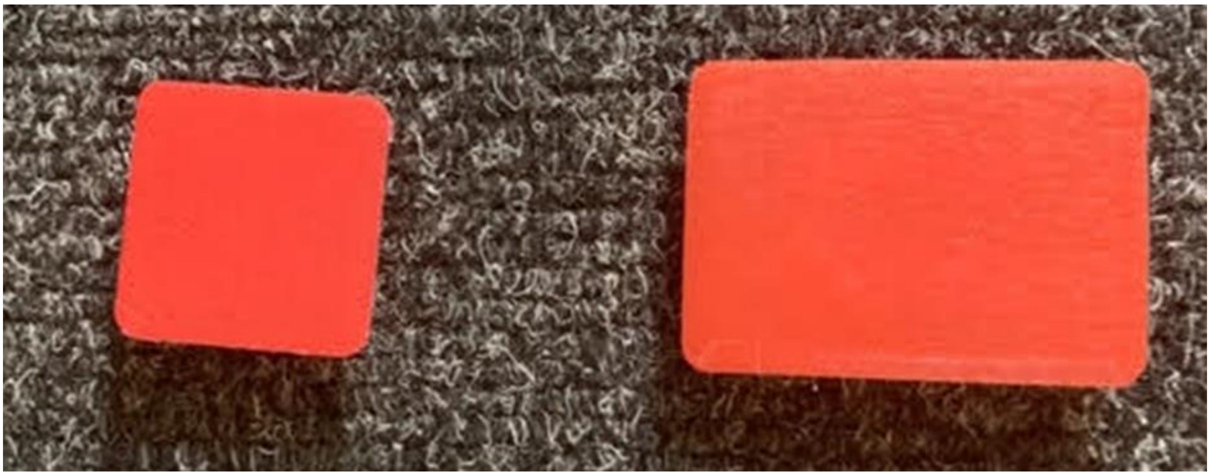

Figure 26: Brackets for Fault Simulation

4.2 Verification results

As mentioned in the previous chapter most of the data was acquired from the Arduino main controller. This data was essentially from the encoder readings that provide a certain position of the demonstrator on a set length of the rails.

For other tests an observation procedure was made, measuring tape and a marker for the locations were used. For the electrical environments a voltmeter was used.

For the data acquired from the Arduino an extension for Excel was used this was PLX-DAQ this help a normal spreadsheet to read the serial port of an Arduino. Also, the following code was implemented on the main controller:

```
void SendData() {

Serial.print("DATA,TIME,TIMER,"); //writes the time in the first column A and the time since the measurements started in column B

Serial.print(Adata); //sends first amount of data

Serial.print(Bdata); //sends second amount of dsta

Serial.println(...); //be sure to add println to the last command so it knows to go into the next row on the second run

delay(100); //add a delay

}
```

This will send to the Excel that has to be with the PLX-DAQ extension active to work, also as this is serial communication, the computer was connected to the Arduino all the time.

4.2.1 Reliability

The results for the first set of test that affects the requirement REQ 01.1 to REQ 01.8 that have to be with the reliability of the system were conclusive and determinate that the system is reliable.

The demonstrator was shown in the RIA conference at Telford proving that it was movable, the device was packed and taken from Cranfield University to the conference without any major problem.

During the test repeatability was demonstrated as it was running around 10 tests per requirement and there were at least 20 requirement were the demonstrator has to show its capabilities, this means that the demonstrator can execute 200 repetitions without crashing or having problems in the functionality.

The functionality of the system is friendly as any person can used it, this was proved at the RIA conference, participants of the event that were not related with the project were able to manipulate it and execute several repairs without much intervention of the experts. This demonstrate that the device is very easy to use.

The repairs were executed without intervention of the any operator as the communication between the robot arm and the main controller was tested and passed without problems. 10 repetitions of a repair was execute and the demonstrator was able to perform without intervention.

The capability of the system to be modular was tested and successfully pass as the central controller was disconnected and all the systems were working separately, in order for them to work a small signal was deployed in each of the subsystems, this simulate the signal given by the main controller. Each subsystem was tested 10 times and all of them worked with no interruptions or major difficulties.

4.2.2 Autonomy

For the requirements REQ 02.1 to REQ 02.6 the principle objective was to validate the autonomy of the system. In order to achieve this several test were developed, one of the most important was the discharge of the battery, assuring the autonomy and independence of the system.

The battery was connected to a load of around 10A taking in consideration that for the motors a voltage of 14V is required the minimum voltage deployed from the battery should be 14V. This was taking in consideration the power required for the system that was not more than 140Watts. This was plotted in Excel and kept track of its discharge. To assure a good autonomy of the battery, it should last a minimum of 1 hour. Figure 27 was obtained after 6 discharges and what shows is the power given in for each discharge.

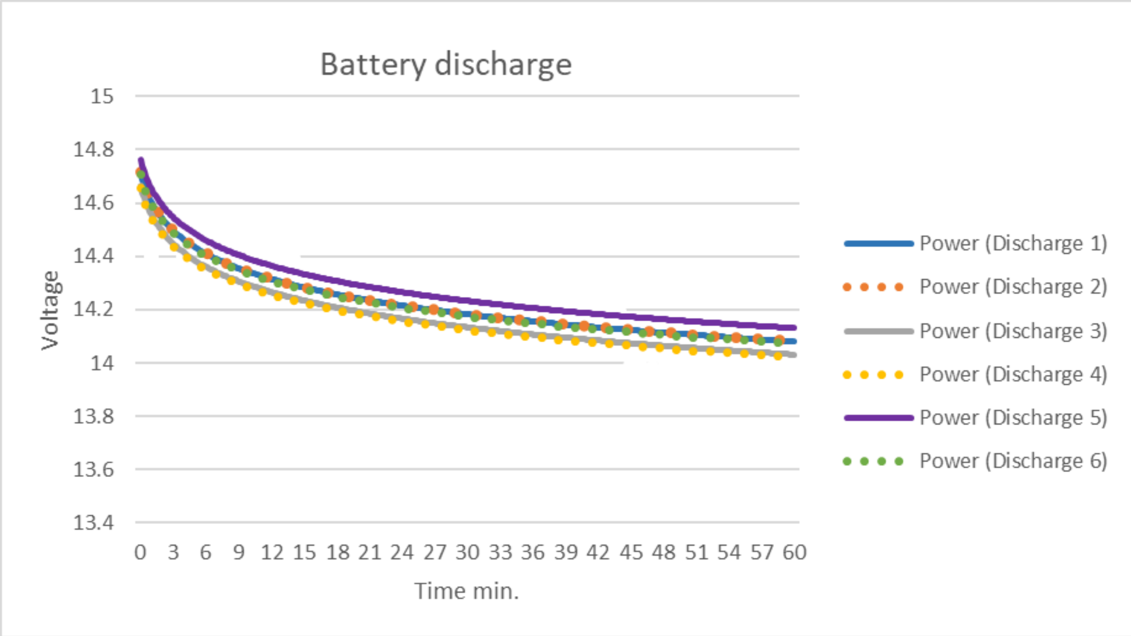

Figure 27: Battery Discharge Rate Test

As can be seen on the Figure 27, the battery will still give at least 14V for one hour, this is because the low load the subsystems required and also because this is 20000mAh LiPo battery.

The small variation of the measurements was because of the charge of the battery, three out of six the battery was discharged and the system start to behave poorly reducing its capability to power all the systems, this can be seen in discharge 2, 4 and 6.

For the movement of the entire demonstrator the main controller has to be fully powered, the amount of current needed for the system was minimum and not overpassing the 10A this assure that the complete system is autonomous and does not require any external action.

4.2.3 Control systems

In order to pass the set of requirements REQ 03, 8 different sections was made. The most important is the main controller, this should have the ability to control all the subsystems, and the most important part is the ability to send appropriate signals for the subsystems to work.

As can be seen in Figure 28 the outputs and inputs of the main controller are synchronized and are making the process complete the fault reparation. There are several signals to take into consideration. The first is the start button signal, this is a physical switch that allows the cycle to start. If the demonstrator is located in home position the train will start motion to the front searching for the first fault but if the demonstrator is located in any other position, the first instinct will be to locate itself in home position, moving backwards until achieve the desired position.

After reaching home position the start bottom should be pressed again to start the fault search, once the fault was detected the motion is backwards again to give space for the robot arm, it will achieve a position and a signal to the process of the robot arm will initiate.

Once all the process is completed the system will ask to press the start bottom to continue with the process once more.

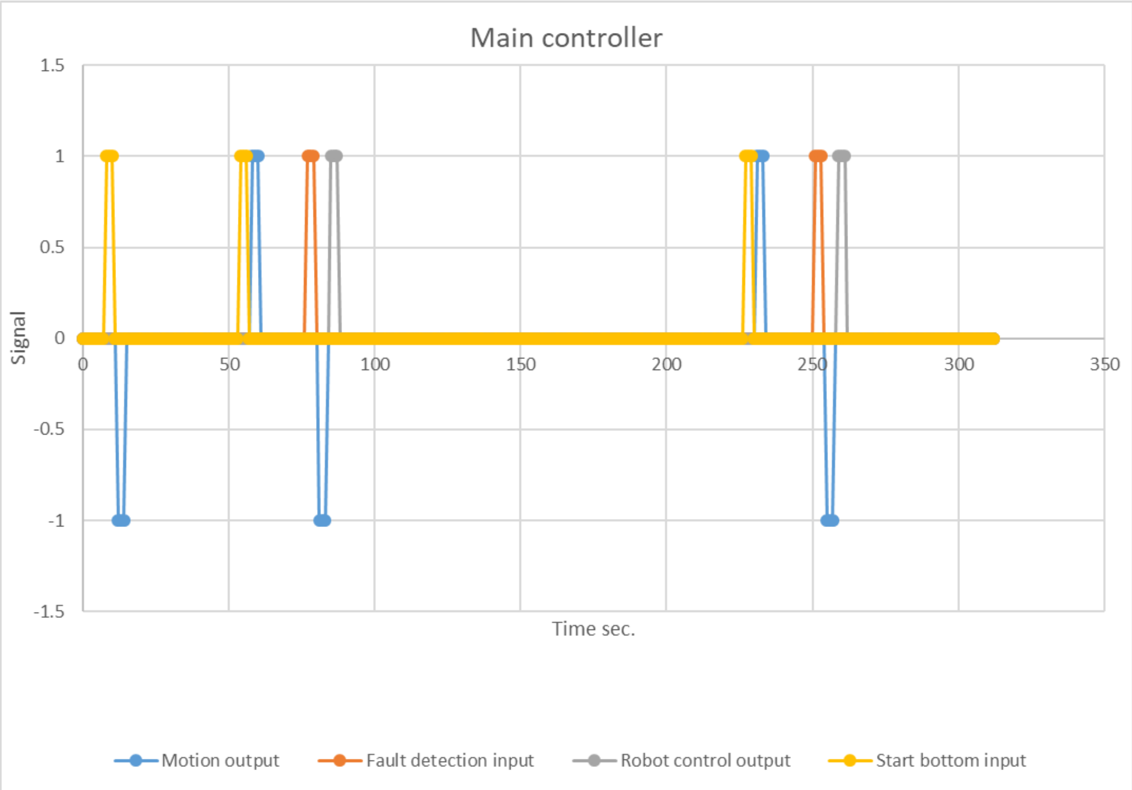

Figure 28: Main Controller Performance Test Results

The pre-repair position is crucial as this will be the start for the X axis for the job of the robotic arm. The minimum distance should be around 16.5 cm back from the fault detection. Figure 29 will show the error faced when going backward for the pre-repairing position.

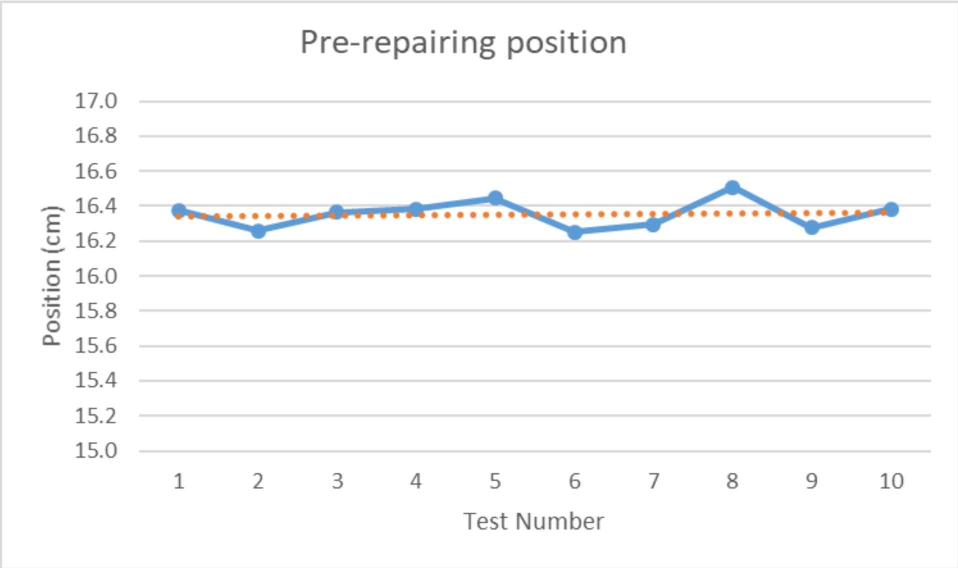

Figure 29: Pre-repairing Position Test Chart

As can be seen in the previous figure the average distance for the pre-repairing position is 16.4cm which is enough space for the robot arm to operate, this will probe the communication between the motion and the main controller.

Another point for the validation of the control systems is the ability to detect the end of the track this value is set up at the main controller as a constant value, this can be changed depending on the total length of the track, the complete measurement should be multiplied by 112 and the value obtained should be placed at:

```
long climit=23000; //Max displacement
```

For the test a value of 23000 was taken that is equal to 205 cm. To make this more autonomous, a proximity sensor should be incorporated, this will help not only to avoid a crash at the end limit but at any other point in the track.

To finalize this control system verification a test of the hand held device was made, this sending different commands to the hand held device and testing its display on the GUI generated for the demonstrator.

4.2.4 Accuracy

This part of the demonstrator V&V was crucial for the repair procedure. In order to achieve precision on the repair an accurate location of the robot arm should be achieved, giving it a good operational area and a good location for the 3D printing process.

For this the fault detection is a key factor, the first fault was located 46 cm from home and the camera should detect it with an error of a maximum of 0.5 cm. Figure 30 shows the tests made and the data recorded from the main controller.

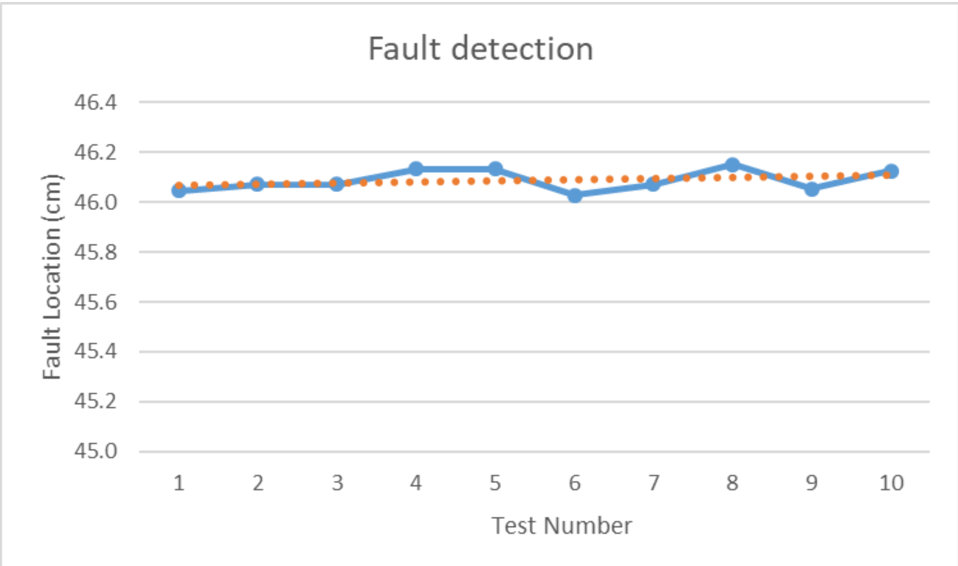

Figure 30: Fault Detection Test Results

As can be seen in the previous figure, the detection of the fault is very precise, the average error was about 0.1cm giving the demonstrator a good first location to allocate the robot arm in an accurate position to work properly. It is important to take into consideration that these values were taken with a level of a maximum ±0.01 degrees, a slight change on this will have a drastic effect on the detection, as the inertia of the movement of the train will cause a misreading of the real position.

To have a good position in the X-axis the demonstrator should be placed in a minimum of 29.6cm and a maximum of 30cm from the home position giving enough retraction and a good space for the robot arm to operate. Figure 31 shows the data obtained from the main controller at the moment of retraction and the location of the X-axis.

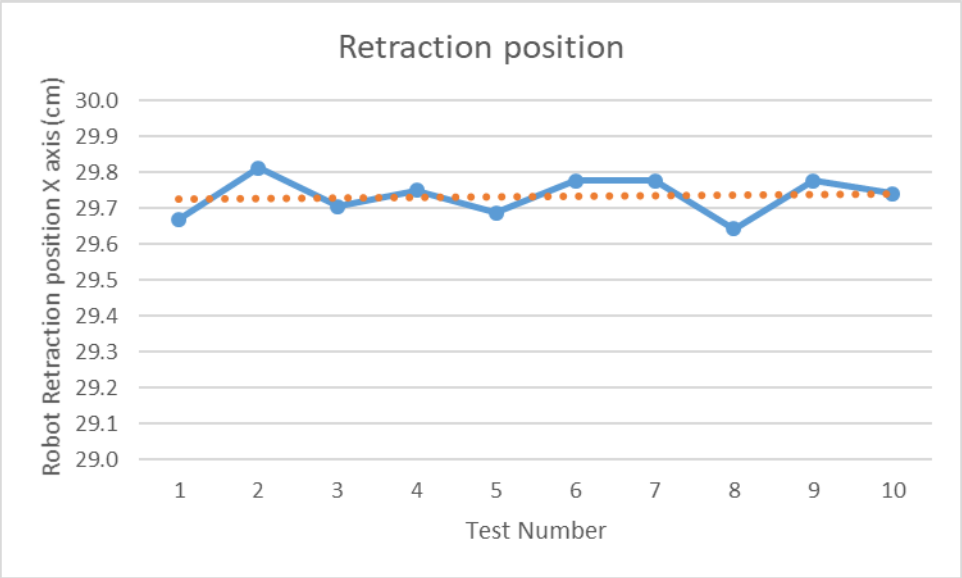

Figure 31: Retraction Position Test Results Chart

The figure shows that the medium error is around 29.7cm from the home position, this is a 0.1cm from the minimum and in range of success printing on target, the importance of the alignment of the rail is crucial for the development of the demonstrator.

For the Y-axis the measurements were taken by observation and helped with a measuring tape, also data from the G-Code was obtained and compared with the data obtained from observation to give precise information. The error was not determinant for a bad location and was in the range. The robot arm should locate in a maximum of 1.7cm and a minimum of 1.3cm from any of the edges of the bracket this will reach the middle of the bracket. Figure 32 shows the results of the test generated for the Y-axis.

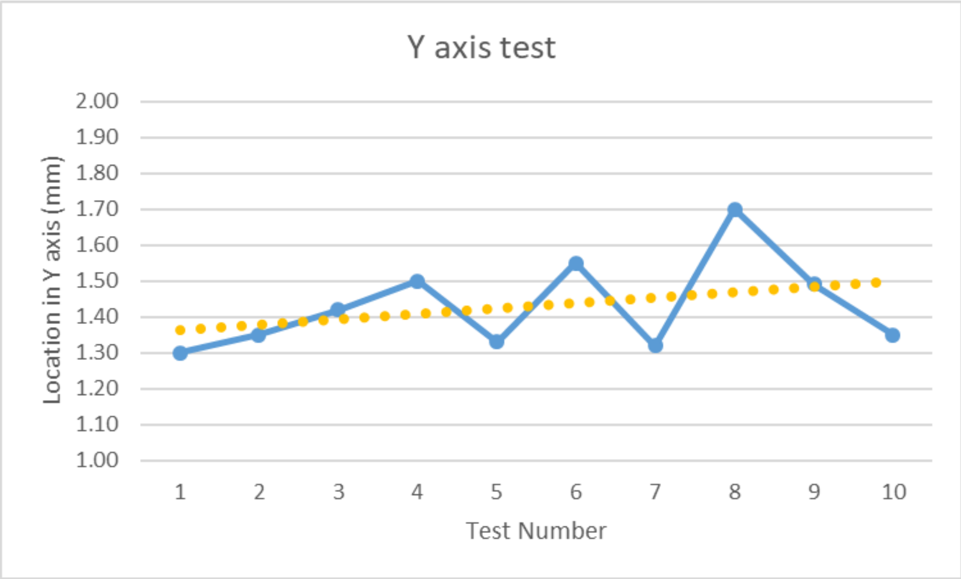

Figure 32: Y-Axis Position Test Results Chart

The medium average of the Y-axis location is in range of the conditions established for the V&V, the point that takes the attention is that the error tends to increase proportionally to the repetitions made. This will be a challenge if the repetitions are more than 20.

The most important axis to take in consideration in the Z-axis as this will establish the first contact with the 3D printing surface, this should be the most accurate position as the filament for the first layer of printing should be as close as possible to the printing surface to stick it and generate a base to create a figure.

Sadly as this is the last part to make a move, all the errors on the other axis will affect this one making it a critical element to take into consideration a minimum of 0.7mm and a maximum of 0.8mm was established as a condition. Figure 33 shows the results obtained for the Z-axis.

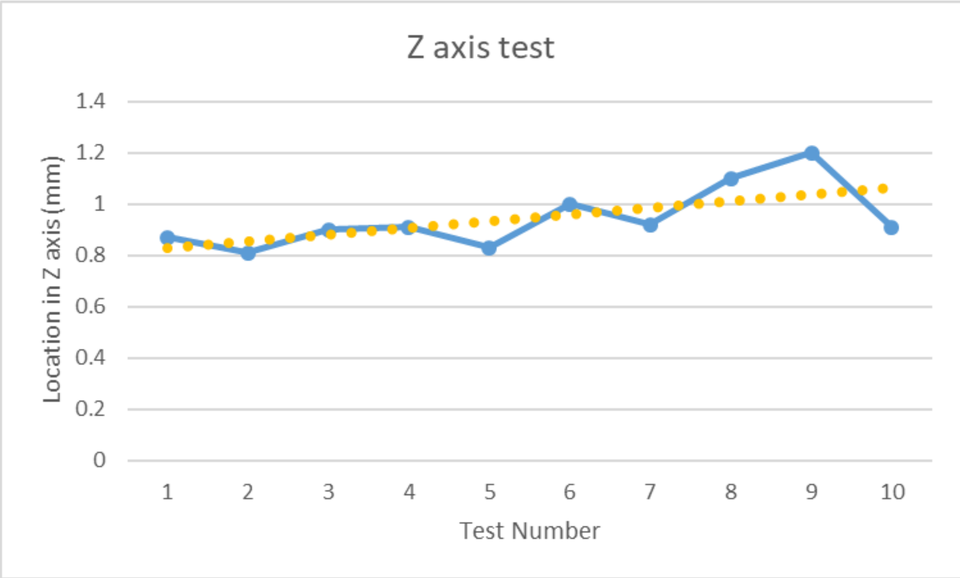

Figure 33: Z-Axis Position Test Results Chart

The Z-axis is affected as a result of the summary of all the other errors, with more than 0.8mm the filament won't stick to the base and the result will be a deformation of the 3D printing process, sadly as shown in the previous figure the median error is starting at 0.8mm but increasing rapidly making the process very complicated to achieve. For this reason the Z-axis location couldn't pass the tests elaborated. It can be solved by the installation of a proximity sensor that will give feedback to the controller and mitigates the error and allows a better positioning in the Z-axis.

As mentioned before if the Z location is not accurate the 3D printing process will fail, the solution taken for the test was to extrude a certain amount of filament and give the robot arm a motion in X and Y, this will be an interpretation of the process but is not actual 3D printing.

4.3 Validation results

As part of the project the physical demonstrator was an exhibit in different conferences for example RIA 2019 and Rail Life 2019. A way to validate the real appreciation of the RIRS for the rail industry was to give a small survey to the assistants asking their point of view and validating it with the scope of the demonstrator.

The questions for the survey were decided by the objectives of the physical demonstrator, taking into consideration the adaptability of the system, the implementation and the industry needs. The final questions were:

1. Do you think this demonstrator truly represents the concept of an autonomous rail repair system?
    a. If no, how do you think the demonstrator can be improved?
2. On a scale from 1 to 5. How valuable are hardware demonstrators to visualize a design concept and anticipate real-life rail problems?
    a. Comments
3. On a scale from 1 to 5. How valuable are technology hardware or software demonstrators to save time and money?
4. On a scale from 1 to 5. How the conceptual hardware demonstrator does adhere to the rail industry's long term strategy?
5. In a scale of 1 to 5, how well does the demonstrator executes:
    a. Autonomous Repair
    b. Fault Search
    c. Payload positioning
    d. Repair and Return to Base

The results of the survey were positive for the scope of the RIRS physical demonstrator as shown in the next figures (Figure 34-Figure 41).

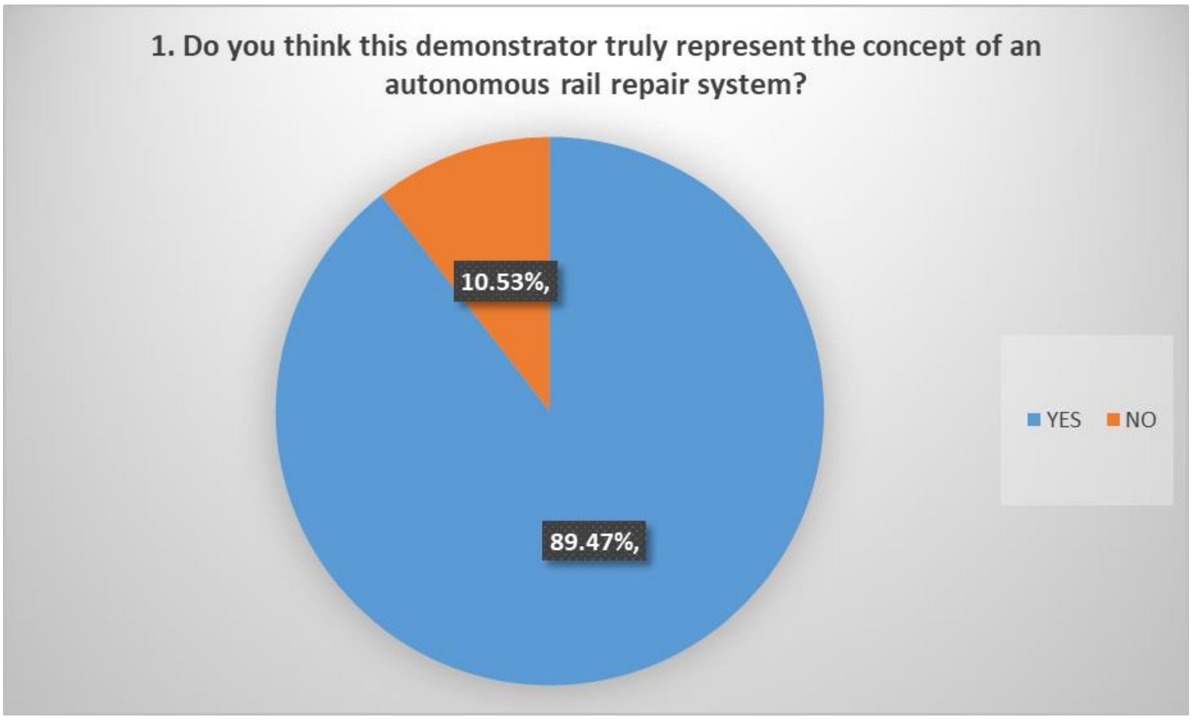

Figure 34: Question 1 of the Survey Result Chart (+ve)

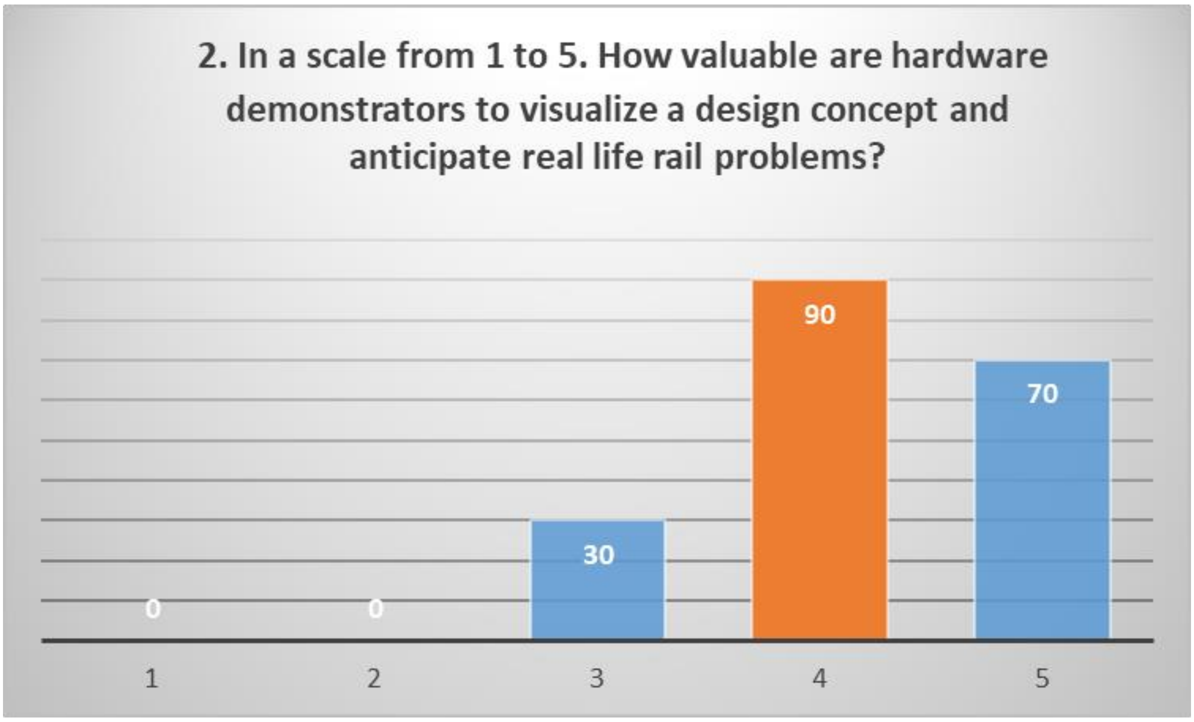

Figure 35: Question 2 of the Survey Result Chart (+ve)

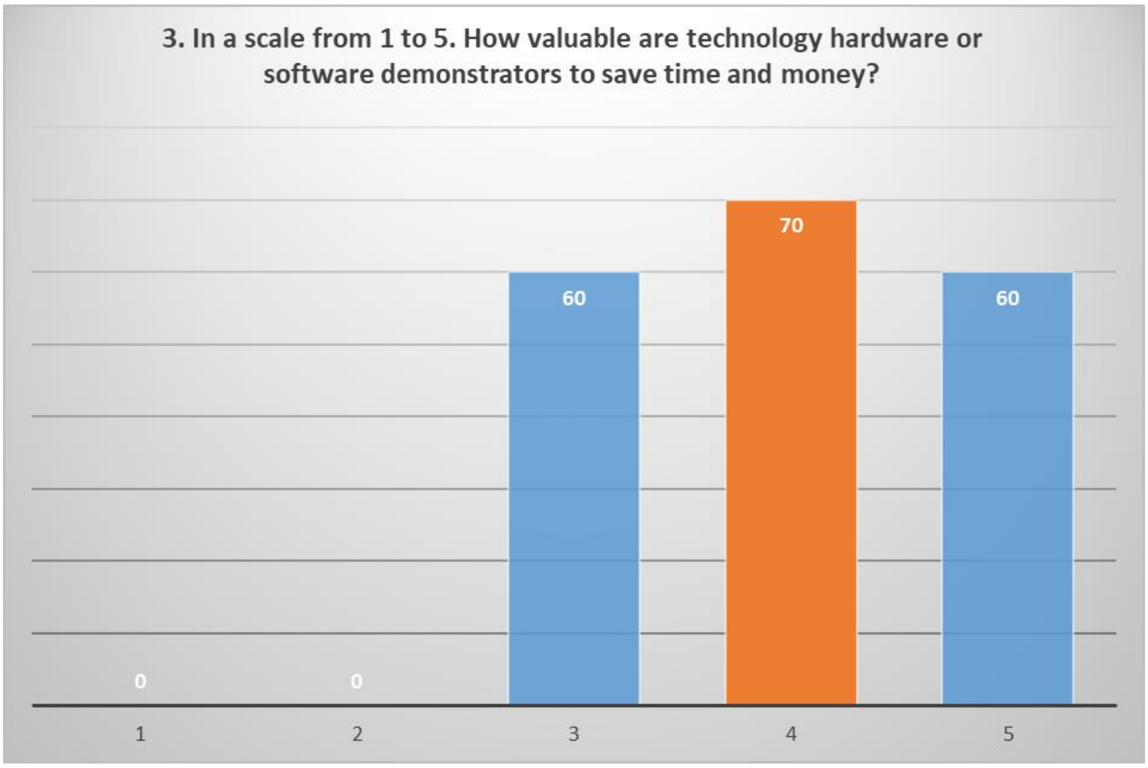

Figure 36: Question 3 of the Survey Result Chart (+ve)

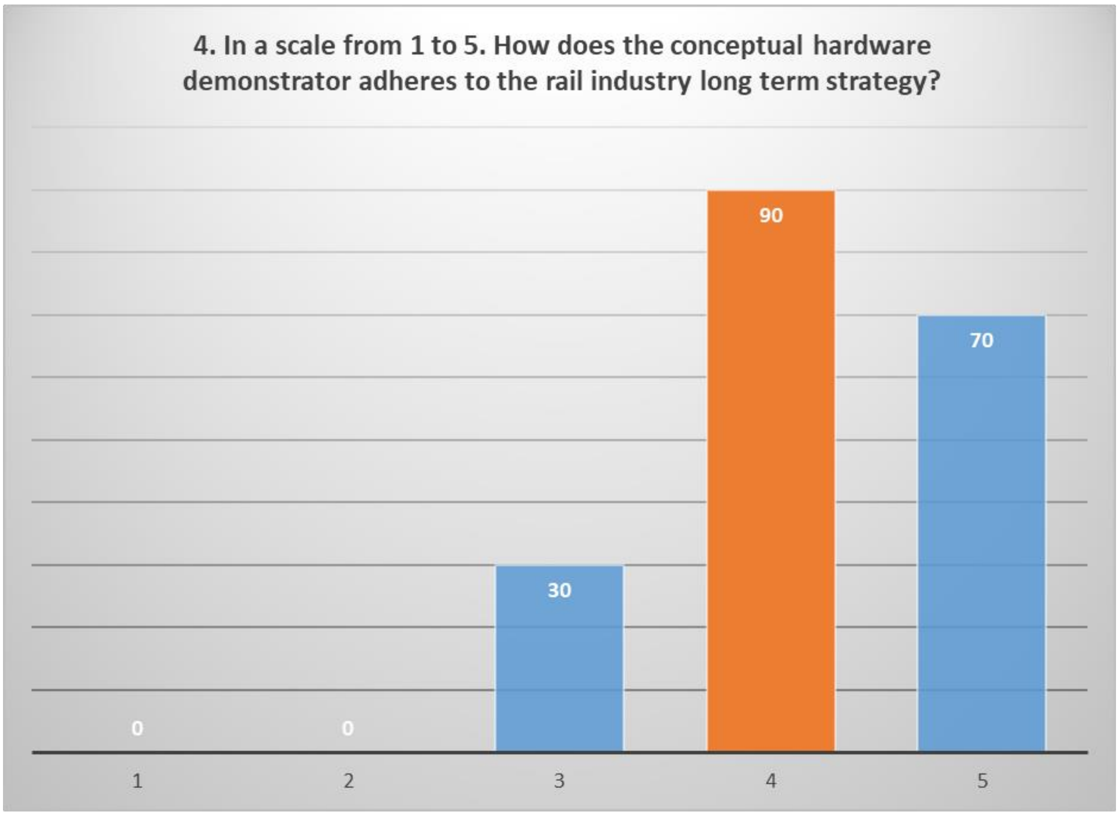

Figure 37: Question 4 of the Survey Result Chart (+ve)

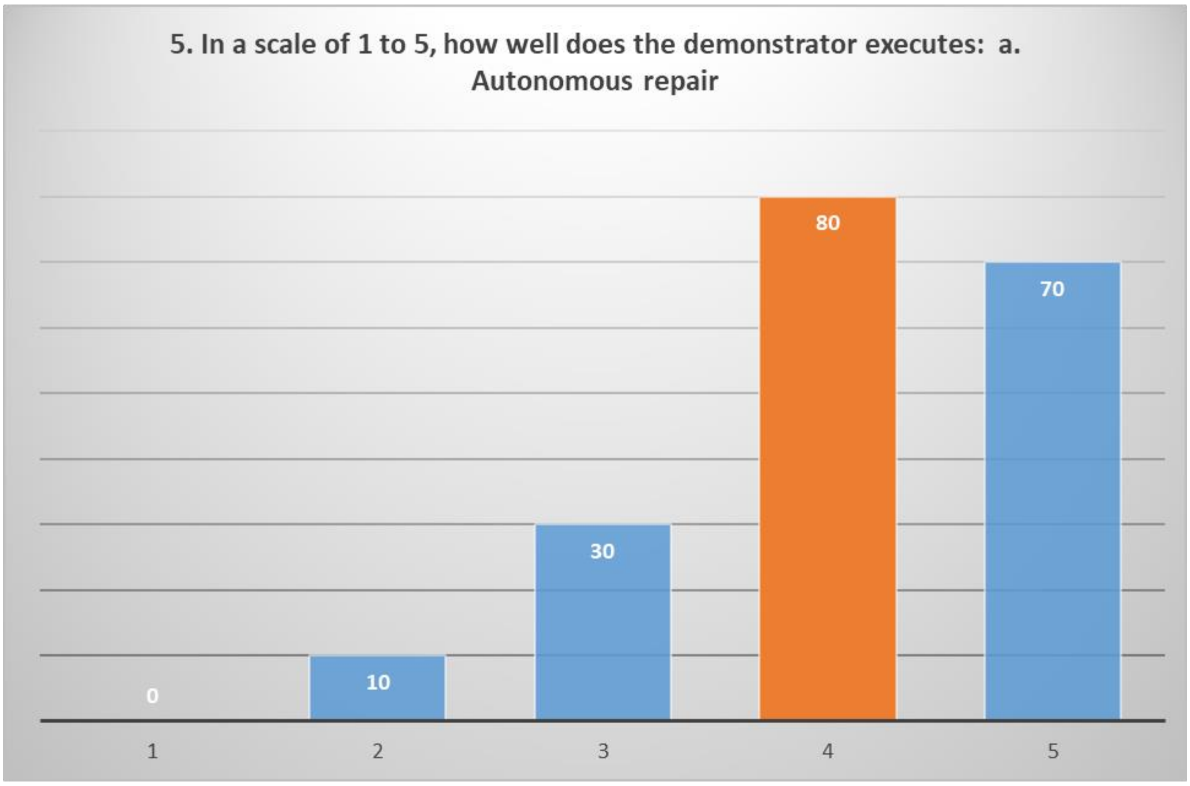

Figure 38: Question 5a of the Survey Result Chart (+ve)

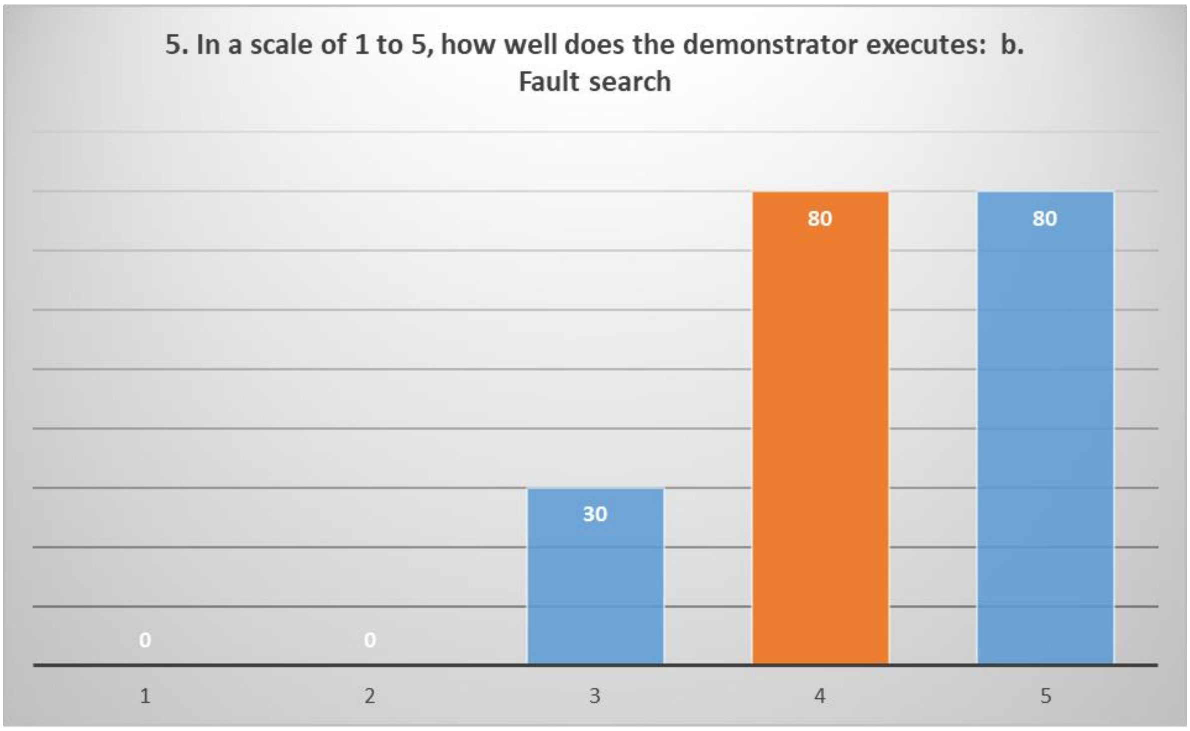

Figure 39: Question 5b of the Survey Result Chart (+ve)

Figure 40: Question 5c of the Survey Result Chart (+ve)

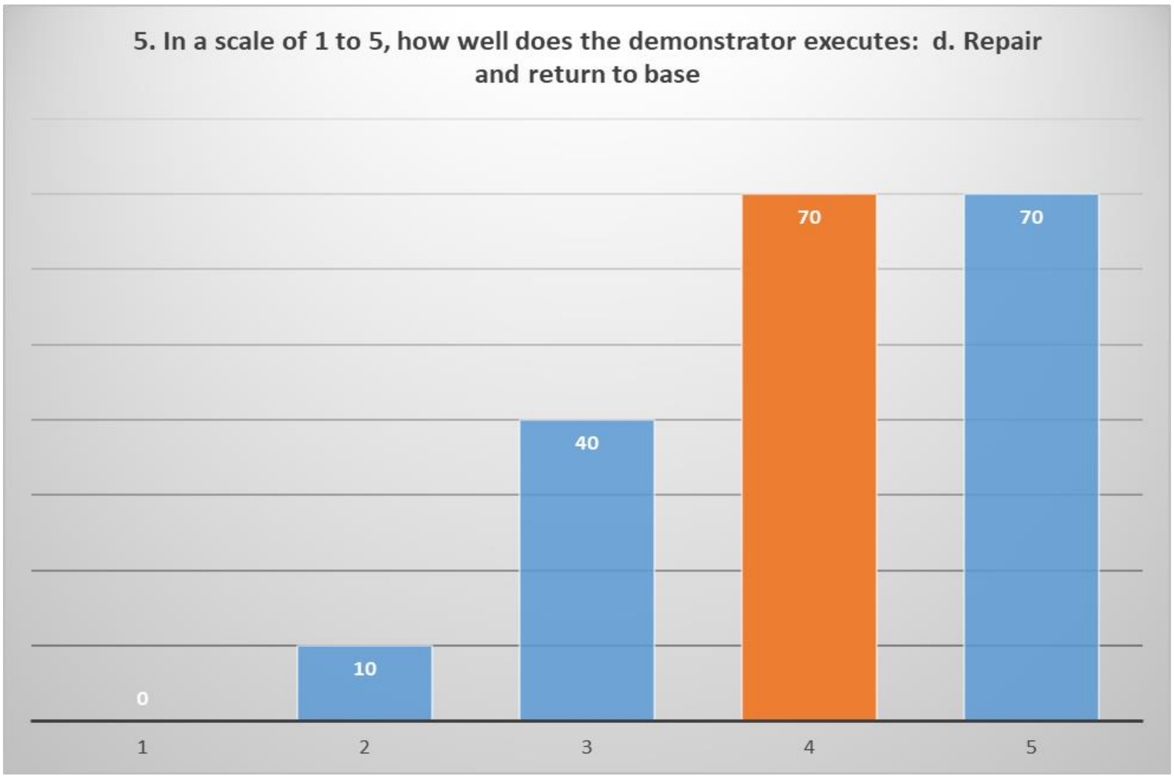

Figure 41: Question 5d of the Survey Result Chart (+ve)

4.4 Final result from the V&V

To finalize the V&V of the RIRS physical demonstrator is important to notice that the objective of this was to determinate if the device was a good representation of the complete RIRS system, giving a more realistic approach to the development of this new technology, to certify this the following conclusions were made:

- Based on the results obtained for the reliability of the physical demonstrator is accurate to say that it is reliable and has a solid construction suitable for conferences where the overall idea of the system can be shown.
- According to the requirements for the autonomy of the system, the demonstrator has shown great autonomy making it more realistic.
- The controls of the system are well integrated and can be easily changed at any moment, a handheld device is a perfect option for displaying the process of the demonstrator.
- There are key factors to take into consideration for the good performance of the demonstrator and one very important is rail leveling. The importance of this will determine the success of the repair.
- The 3D printing process can be done if the task is not complex, meaning that the demonstrator is capable to extrude lines but not to print a complete shape, this due to the different error accumulation. This is understandable and expected as the robot arm is not in a fixed base and the slight difference in position will have a big effect in the 3D printing process.
- The lack of feedback to the controllers may be a cause of research as for further implementations a better sensor system should be taking into consideration.

It can be said that overall the demonstrator fits the technology readiness level 3 that is “Proof-of-Concept Demonstrated, Analytically and/or Experimentally”. There are several observation and recommendations to make to advance in the TRL scale:

- The location of the demonstrator should be better monitored using a positioning sensor and other types of communications. For a larger scale would be interesting to check the possibility to add ERTMS communications to this type of system.
- The end effector should be placed with more precision, this can be achieved with the integrations of precise proximity sensors. For a larger scale the implementation of this type of sensors is critical and more than necessary.
- For the safety of the device, the user and spectators a series of ultrasonic sensors should be implemented for obstacle avoidance or to not hit the end of the track.

In conclusion, it is accurate to say that the demonstrator is capable of proof the general idea of the RIRS and shows the multiples advantages that this technology will carry to the rail industry.

5 Scalability of the system

This chapter is dedicated to finding the correct scalability procedure and following it to advance with the project and have a more robust and reliable prototype to incorporate the technology into the rail industry.

For achieving a better Command and Control System for the RIRS, several decisions were considered and placed as probable solutions for the scalability process of the Robot Inspection and Repair System.

The steps to complete the scalability process were:

- Definition of the scalability method
- Decide the key requirements to be accomplished
- Generate a concept proposal

Based on the meetings with the stakeholders of the project, some new requirements and scopes were selected. The scalability process and its results are displayed next.

5.1 Definition of scalability method

Scalability has become increasingly relevant in recent years as technology has made it easier to acquire more information and data for different systems making it easier to develop better solutions to incremental needs.

Scalability refers to the degree to which the functional and performance of a system are size agnostic. This translates to the capacity of a system to support a larger or smaller workload, connections, functions, or external software services. Scalability is a short-term operational metric of evolution that applies to performance. In practice, scalability then is the degree to which a system can maintain its performance and function, and retain all its desired properties without a corresponding increase in its internal complexity (de Weck et al., 2011). There are two important differences between scalability in the platform. To start, we normally think of scalability as the capacity of a system to scale upward. However, in platform settings, the capacity to scale downward is just as important.

Therefore scalability must capture the system's capacity to expand or contract, upward or downward (Parnas, 1979).

To adapt scalability with the scope of the project, a definition was needed. Many scalability meanings can define what the project aims to accomplish, but the definition used is the one at describes scalability as a characteristic of a system, model, or function that labels its capability to cope and perform well under an increased or expanding workload or scope. A system that scales well will be able to maintain or even increase its level of performance or efficiency even as it is tested by larger and larger operational demands.

Also is important to underline what will be scaled on this project as the RIRS will be implemented in the rail industry. The bases of having a robust Command and Control System is key in the scalability of this project. Scaling the CCS will be considered as for this software scalability can be applied, some several papers and books describe the different methods of scalability for software and control.

Another way to scale the project will be talking about the size of the demonstrator itself, having a system suitable for the real industry requirements. This means that the physical demonstrator is capable to inspect, detect and repair a real rail fault. For this a preliminary design for a bigger machine is needed, this will scale the hardware of the project making it robust to work in rough environments and autonomous.

The scalability of the project can also be focused on the increment in the TRL's making it a higher number that will make the project suitable for the industry. Taking into consideration that the increment on the TRL will also perform an increase in the hardware and software of the project, the scalability was focused on this.

5.1.1 Decision making for scalability path.

Knowing all the possible ways the scalability of the system can take, only one path can be chosen due to time, importance and the results provided by the validation and verification process. It was important to select a path as it will dictate the requirements for the future work that will be made into this project.

Having all this together a decision-making chart was implemented in other to select the correct path taking into consideration all the parameters required to develop a scaled prototype for the RIRS.

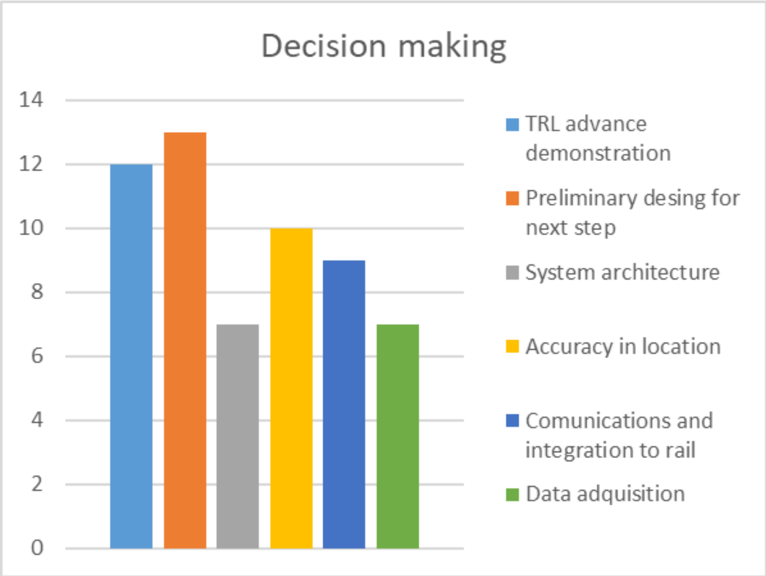

Figure 42: Decision-making chart

The previous char shows the importance of the different paths that the scalability can be applied. Having as criteria the first requirements from the stakeholders, the Cranfield scope, the project scope, the applicability and the V&V results, the selection of advance on the TRL was selected but taking consideration that a preliminary design of the software and hardware will be included in this path. Also this will give a basic idea of the implementation of robust systems in localization and the CCS structure.

5.2 Scalability scope

The path of the scalability was selected and with this the consideration of advancing on the TRL was decided. For this it was important to define the actual Technology Readiness Level of the RIRS physical demonstrator. The level of the physical demonstrator is key to continue the scalability of it.

The TRL of the physical demonstrator and its following development will follow the considerations of the rail industry, for this, the evaluation of the technology readiness levels has its specific parameters different from the TRL develop by the NASA.

The technology readiness levels for the rail industry were created by the Network Rail bases. The criteria for the TRL created by Network Rail include different sides, is the engineering part, this one oriented to develop the technology side of the project and focused on the new advances the technology will bring in terms of engineering.

On the other hand, the TRL shows a financial part of the project taking into consideration market expectations, budget and probable cost of development. This part of the TRL will not be included in the scalability of the project as the main objective of the RIRS for this thesis will be the advance on the technology including the engineering systems.

Once the TRL of the physical demonstrator is defined, a maximum upgrade of it can take into consideration, due to the different requirements to be accomplished for advance in the TRL the financial and marking side of the levels will be neglected but will be noted as pendent for future work.

5.2.1 TRL gap assessment tool

To define the technology readiness level of the physical demonstrator a tool created by a previous student was used. This tool is an application that could assess the gaps in the TRL process automatically, with the identification of activities and skills needed to fulfill them.

It is important to underline that in the TRL process there are several requirements to satisfy and the tool was based on the requirements of the railway industry, linked to Network Rail's project. The maximum level will be towards TRL 7 as this is a requirement and a limitation of the project scope. Its applicability is therefore linked to the industry and projects in this area.

With this tool, the physical demonstrator will be able to evaluate a particular TRL level, identify gaps and underline competencies needed in the development of complex innovative projects.

The tool was developed in Excel by using VBA language. This helps the user to give inputs for the system and an algorithm will calculate the level automatically by the inputs of the user.

All the inputs of the user are guided and with simple clicks, on specific buttons the program will generate a final report explaining the level achieved and the gaps on it to fulfill previous or next levels.

In the tool there are 49 user forms, in particular:

- 43 for the TRL requirements, each requirement is presented by one user form.
- 1 to present the activities and skills
- 5 to present the beginning of the assessment and the first choices

Every user form represents a way to interact with the user, therefore the concept was to create a path in the theoretical assessment process on how the user will interact with the tool. Information, data and checkpoints are shown by the visual form where you can put details or make a choice.

The use of this tool helps to the definition of the correct TRL of the physical demonstrator. The last update of the physical demonstrator onto this tool was the 05/06/2019 and showed that the TRL is 3 but due to the work done with the validation and verification of this system, some aspects of the TRL4 and TRL5 were made, but as a TRL number is obtained once the description in the diagram has been achieved the current TRL of the demonstrator is TRL3. Figure 43 shows a part of the tool report, find the full report on the 7Appendix B.

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7
100%	100%	100%	50%	25%	0%	0%

Figure 43: Tool result for current TRL

Once defined the real TRL of the demonstrator it was important to focus on how can this be scale into a certain level where the project can be executed and cover all the requirements for a higher TRL.

The tool report also gives the gaps found on the different TRLs so to follow the scalability process the following gaps were considered:

- For complete TRL4:
    - Identification and quantification of technology risks
    - Risk Reduction Plan
    - Interface testing and initial integration
- For complete TRL5:
    - Development, acquisition, and access to the trial and test facilities to validate the technology
    - Produce 'Models' to be used in validation testing.
    - Technology Support Plans
    - Technology integrated with the system establish the boundary conditions and interfaces documented

These are some of the consideration to be made to advance in the TRL the goal is to reach TRL7 and keep the project suitable for the rail industry, from Figure 44 is visible that there are several areas to improve, as mentioned before the areas were financial or marketing tools are required, were not considered as this thesis will cover the scalability in the TRLs for the hardware and software of the RIRS.

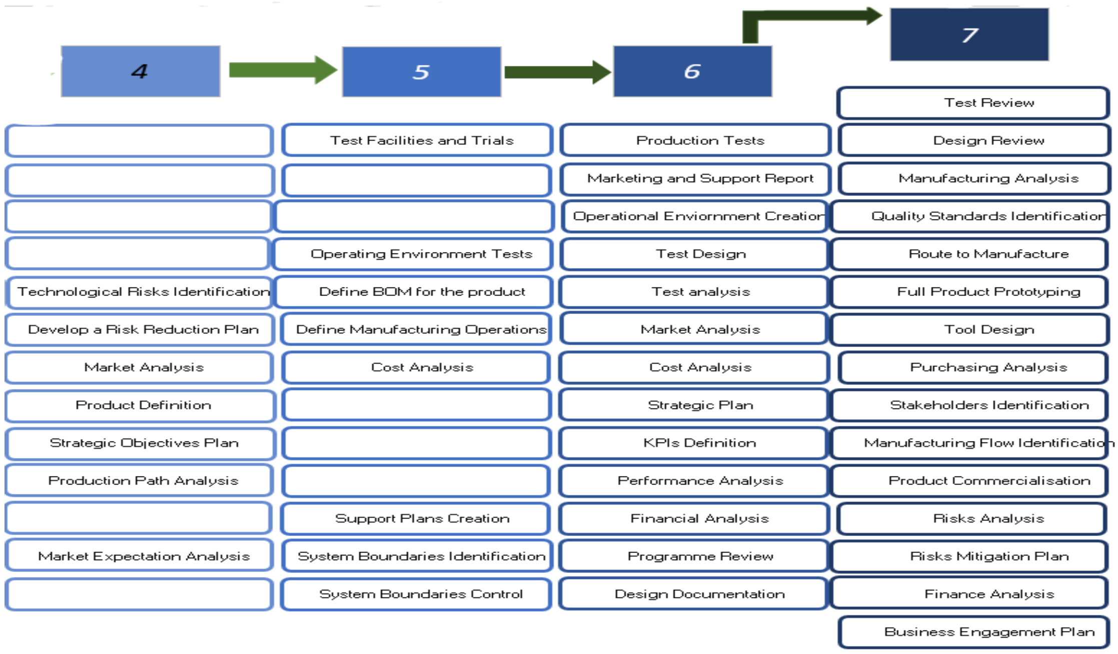

Figure 44: TRL assessment tool results

5.2.2 Scalability requirements

Once the starting point was defined with the knowledge gain from the TRL gap assessment tool, the following step will be the requirements for the scaling procedure.

As mentioned in the previous chapter, there are some different requirement for advancement in the TRL, one is the Test Environment, this will allow the RIRS to be fitted into the rail industry, generating the tests can be confusing as this ones can be made on scale bases taking in consideration the actual physical demonstrator or can be made on a real environment where the conditions of the test are optimal for the replication of the functions of the CCS and the RIRS can be tested.

Having a real environment requires that the system gets on the real rail, as the physical demonstrator is 11:1 scale has a simple structure to follow and scale it to a 1:1 and test it on a real environment.

The following requirements are the most important to cover and will apply for the development of a surface and system that can be tested on a real environment and is capable to perform all the previous requirement that defines an RIRS. The complete list of the requirements can be found in the 7Appendix A section.

Table 3: Scalability requirements

ID	**Parent**	**Name**
REQ0001	REQ0001	REQ0001 Effectiveness, Performance & Suitability
REQ0002	REQ0001	REQ0002 System Effectiveness
REQ0006	REQ0001	REQ0006 System Performance
REQ0010	REQ0001	REQ0010 System Suitability
REQ0003	REQ0002	REQ0003 Geographical Coverage
REQ0004	REQ0002	REQ0004 Network Disturbance
REQ0008	REQ0006	REQ0008 Navigation Accuracy

The requirements mentioned are based on the development of a new demonstrator that can be fitted on a real rail environment, this can help understand the limitations and the challenges that the RIRS will face and will scale the TRL.

The most important features of the new demonstrator are that:

1. The demonstrator will be capable to go on and off-track at any point
    a. Due to safety, the demonstrator will be able to position itself on tracks and easily get off the track to the 10ft or the CES.
    b. If the RIRS will be transported to the location of the possession the demonstrator is capable to autonomously position itself for the task needed.

2. The location measurement is critical and needs special consideration as the difference in metrics can have a crucial effect on the inspection and repair process
    a. The fault can measure microns on a kilometer range, this requires precise localization and detection
    b. The location should be registered and kept track in case of preventive maintenance and future analysis.
3. The CCS of the demonstrator should be robust and meet the new technologies as ERTMS.
    a. The command and control system should be capable to receive upgrades for the new technologies emerging in the rail industry.
    b. ERTMS compliance will be an advantage as the rail industry is working hard to go towards this new technology.
    c. The software that controls the RIRS should be modular and adaptable for different integration proposes.

Knowing all the requirements for the scalability of the RIRS into the development of a higher standard demonstrator. The software and hardware will be affected as the scalability of the project require that the system is tested into a real environment to continue with the V method and continue the development of this kind of technology.

5.2.3 Command and control system scalability.

The CCS is a key factor to be considered in the scalability of the RIRS as it is the main controller and will dictate the correct procedure to follow to achieve a correct rail inspection and repair.

The actual framework of the CCS is based in Arduino and Raspberry's controllers meaning that the source code is not reliable or can not be put on a firewall capable to protect it. The idea of generating a better code and system for the main controller is a key factor in the development of a bigger scale element. The framework for the new CCS should be considering a robust controller for robotic applications one operating system like ROS.

Developing such control will assure that the control is robust enough for industrial purposes. There is ROS-Industrial that is an open-source project that extends the advanced capabilities of ROS software to industrial relevant hardware and applications. This operating system is highly recommended for a project like this and fits the scope of the scalability of the system.

5.3 Scalability procedure

The scope and requirements of the scalability were already selected, also the subsystems that will be affected by this process have been considered. The process of scalability was made by finding the components needed to comply with the TRL requirements.

The procedure was to divide the project into two main subjects:

1. Hardware: That will incorporate the physical components of the RIRS such as the mobile unit, the robotic arm, the cameras and the GPS.
2. Software: That includes the CCS and the control programming that will be considering ROS-Industrial.

Having the parts of the system-defined the process was to develop a complete list of elements that will suit the requirements from the TRL.

This will allow generating a first concept proposal for the initial layout of a new RIRS to be tested in a real environment.

5.3.1 Hardware scaling

The hardware will be the first element to take into consideration to start with the scalability procedure. One key part of the hardware is the mobile unit, as this part is key to accomplish the aim of the RIRS, the mobile unit was the part with most challenges as it has to be able to go on and off-tracks autonomously making it the most sensible part of the hardware system.

Taking into consideration that the first physical model was only mounted on-track, the search for a new mobile unit will be classified as a high priority on the scalability process.

By the requirements, an autonomous mobile unit that can transport a robotic arm on top of it meets the definition of an unmanned ground vehicle (UGV). There are many types of UGV in the market but here is important to meet some requirements of the software systems because the control system should comply with the hardware selected.

Another subsystem that will be a key factor in the scalability of the hardware system is the robotic arm, the importance of having a robotic arm with an exchangeable end-effector is crucial for the selection of this item.

Finishing with the hardware scaling; the consideration of a localization system and vision recognition to make the UGV capable to understand its surroundings and make it able to perform the tasks and maneuver through the field without creating a collision with other items or workers on site. This part is essential as the sensors selected will be capable of performing a good interaction between the humans and the machine.

5.3.1.1 Mobile Unit

As mentioned before the selection of a good mobile unit is crucial for the development of the scalability for the RIRS. The mobile unit will be a UGV capable to understand its surroundings. By definition a UGV is a vehicle that operates while in contact with the ground and without an onboard human presence. UGVs can be used for many applications where it may be inconvenient, dangerous, or impossible to have a human operator present. Generally, the vehicle will have a set of sensors to observe the environment, and will either autonomously make decisions about its behavior or pass the information to a human operator at a different location who will control the vehicle through teleoperation.

Based on this specific application, the unmanned ground vehicle will include the following components:

- Platform: Will be based on all-terrain vehicle design and includes the locomotive apparatus, sensors, and power source. All-terrain wheels will be the form of locomotion. Besides, the platform includes a joint where the robotic arm can be incorporated.

- Sensors: The primary purpose of the UGV sensors is navigation, another is environment detection. Sensors include compasses, odometers, inclinometers, gyroscopes, cameras for triangulation, laser or ultrasound range finders, and infrared technology.
- Control systems: Unmanned ground vehicles are generally considered Remote-Operated and Autonomous, although Supervisory Control is also used to refer to situations where there is a combination of decision making from internal UGV systems and the remote human operator. But as mentioned before the base of the operating system will be ROS.
- Guidance interface: The implementation of several systems will allow the RIRS
- Communication: Communication between UGV and control stations will be done via radio control or fiber optics. It may also include communication with trains and robots involved in the operation via ERTMS protocols.
- Systems integration features: Systems architecture integrates the interplay between hardware and software and determines UGV success and autonomy. In this case the ROS will be having the authority in the software so the integration of this operating system will be a key factor for choosing the correct UGV.

Having all this in consideration, the selection of the UGV was a challenge as the market for this type of mobile unit is mainly military-focused, and the information is limited. Several companies allow the development of new UGV platforms one of them is MILREM and the other is CLEARPATH ROBOTICS. These companies are on top of the research of new sectors where UGVs can be implemented.

The MILREM model has a more military design as can be seen in Figure 45. But it is ROS compatible making it an open-source UGV available to modify the characteristics of it

Figure 45: MILREM Multiscope UGV

On the other hand, is CLEARPATH ROBOTICS that has a wide selection of platforms with different options to take into consideration, all the platforms are ROS compliance and all the other subsystems are available. The most common platform is the HUSKY but there are many options.

Figure 46: HUSKY CLEARPATH ROBOTICS

CLEARPATH ROBOTICS was the ideal selection to consider for the mobile unit now it was time to select between their different platforms:

1. Husky
2. Warthog
3. Jackal
4. Moose

Each one of them is UGV consider for exteriors and is ROS compliant the selection of one of them will be made by knowing which one has the best adaptability to the other systems that will be incorporated into the platform.

5.3.1.1.1 HUSKY

Husky is a medium-sized robotic development platform. Its large payload capacity and power systems accommodate an extensive variety of payloads, customized to meet the research needs. Stereo cameras, LIDAR, GPS, IMUs, manipulators and more can be added to the UGV. The Husky's rugged construction and high-torque drivetrain can take your research where no other robot can go. Husky is fully supported in ROS with community-driven Open Source code and examples.

The Husky has high-resolution encoders that deliver improved state estimation and dead reckoning capabilities. A finely tuned, yet user-adjustable controller, offers incredibly smooth motion profiles even at slow speeds (<1cm/s) and with excellent disturbance rejection.

Husky was the first field robotics platform to support ROS from its factory settings. Use Husky to integrate with existing research and build upon the growing knowledge base in the thriving ROS community to get started producing research results faster. Husky uses an open-source serial protocol and we offer API support for ROS, and options for C++ and Python.

Figure 47: Husky picture from CLEARPATH ROBOTICS

5.3.1.1.2 WARTHOG

Warthog is a large all-terrain unmanned ground vehicle capable of traveling on land and in water. It can handle tough environments with its rugged build, low ground pressure, and traction tires, which allow effortless mobility through soft soils, vegetation, thick muds, and steep grades.

Payload mounting plates and accessible power and communication ports allow Warthog to be easily customized with sensors, manipulators and other payloads to accommodate a wide variety of robotics applications.

Warthog is engineered to go where no other UGV can. Its rugged, lightweight steel and aluminum build gives it low ground pressure and traction to tackle all types of difficult terrains including steep grades and soft soils. With built-in bilge pumps and an IP rating of 65, Warthog is fully amphibious, capable of moving through waterways at speeds up to 4 km/hr.

An onboard PC comes with the open-source Robot Operating System (ROS) preinstalled and configured. Rich documentation, demos and tutorials are provided, along with a 3D simulation model for Gazebo to help you get started quickly and hassle-free.

Warthog’s powerful drivetrain is capable of moving 272 kg of payload and can reach speeds up to 18 km/hr on land. The optional trailer hitch provides ample force for towing massive payloads and industry-standard implements with ease.

Figure 48: Warthog picture from CLEARPATH ROBOTICS

5.3.1.1.3 JACKAL

Jackal is a small, fast, entry-level field robotics research platform. It has an onboard computer, GPS and IMU fully integrated with ROS for out-of-the-box autonomous capability. As with all Clearpath robots, Jackal is plug-and-play compatible with a huge list of robot accessories to quickly expand.

Jackal is built from a sturdy aluminum chassis made with a high torque 4×4 drivetrain for rugged all-terrain operation. It has an IP62 weatherproof casing and is rated to operate from -20 Celsius or +45 Celsius. All connections pass through a compressed-foam cable management port for communicating with external payloads without needing a complex seal.

Add sensors, cameras and other accessories to Jackal’s simple mounting platform. Use the 5V, 12V or 24V power options and easily connect cables to the internal onboard PC. The internal area is available for additional computing power or storage.

Jackal's onboard PC comes fully equipped so you can quickly sync ROS with an RVIZ GUI and Gazebo model. Skip weeks of setup and jump straight into your research with Jackal's extensive demo code. With wireless connectivity via Bluetooth and wifi, Jackal is ready to go every time you turn it on.

Figure 49: Jackal picture from CLEARPATH ROBOTICS

5.3.1.1.4 MOOSE

Moose UGV is the largest all-terrain unmanned ground vehicle yet. It can handle tough environments with its rugged build, low ground pressure, and 8x8 traction tires, which allow effortless mobility through soft soils, vegetation, thick muds, and steep grades.

With a large payload mounting area and accessible power and communication ports, Moose can be easily customized with sensors, manipulators and other payloads to accommodate a wide variety of robotics applications.

Moose's onboard PC comes with the open-source Robot Operating System (ROS) preinstalled and configured. Rich documentation, demos and tutorials are provided to help you get started quickly and hassle-free.

This UGV can integrate third-party sensors and components quickly and easily with flexible payload mounting, easy to access power and reconfigurable I/O (Ethernet, USB, WIFI, etc).

Moose is engineered to go where no other UGV can. Its rugged, lightweight steel and aluminum build gives it low ground pressure and traction to tackle all types of difficult terrains including steep grades and soft soils. With optional built-in bilge pumps and an IP rating of 65, Moose is fully amphibious, capable of moving through waterways at speeds up to 5 km/hr.

Figure 50; MOOSE picture from CLEARPATH ROBOTICS

5.3.1.2 Robotic arm

The robotic arm is essential to develop the task of the RIRS is one of the key elements on all the project as this will be performing not only the inspection but the repair procedure of the process.

Nowadays robotic arms are a well-known territory and several companies have good expertise in the development of these kinds of elements. Companies like KUKA or Universal Robot are the ones that develop robotic arms and can be fitted into the scope of this project. Also, they have enough expertise to ensure the robustness of the robotic arm.

As the mobile unit, the robotic arm should have ROS compliance as this operating system will be selected for the main controller and the CCS. The idea of having ROS implemented on a robotic arm was well tested and can be relied on, also there are several implementations of ROS for this kind of application.

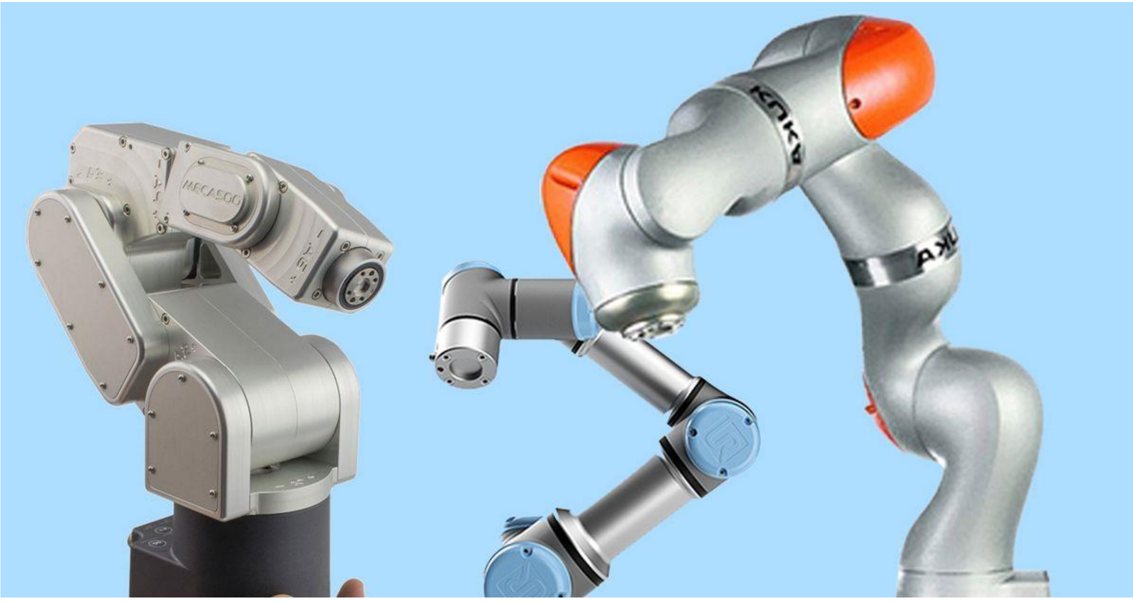

Figure 51: Robotic Arms pictures.

Another key factor od the robotic arm will be the ability of having a modular end-effector, this due to the different tasks that the robotic arm will perform. It is important to note that the robotic arm will be performing not only inspection of the rails but also will perform repair tasks where the end-effector will change from a cama or other inspection system to a more precise repairing tool.

5.3.1.2.1 KUKA

The LBR iiwa is the world's first series-produced sensitive, and therefore HRC-compatible, robot. LBR stands for "Leichtbauroboter" (German for lightweight robot), iiwa for "intelligent industrial work assistant". This kind of cooperative robot allows, humans and robots to work together on highly sensitive tasks in close cooperation. This opens up the possibility of new applications and the way is paved for greater cost-effectiveness and utmost efficiency. The collaborative and sensitive LBR iiwa robot is available in two versions with payload capacities of 7 and 14 kilograms.

Thanks to its joint torque sensors, the LBR iiwa can detect contact immediately and reduces its level of force and speed instantly. Its position and compliance control enable it to handle delicate components without creating crushing and shearing hazards. The lightweight LBR iiwa with its high-performance servo control is able to detect contours quickly under force control. It establishes the correct installation position and mounts components quickly and with the utmost precision with an axis-specific torque accuracy of ±2% of the maximum torque. The LBR iiwa can also find small, delicate components in next to no time without any assistance.

Table 4: Technical Specification iiwa KUKA

System Parameter	LBR iiwa7 R800	LBR iiwa 14 R280
Category	Small Robots (3-10 kg)	Small Robots (3-10 kg)
Payload	7 kg	14 kg
Total Load	7 kg	14 kg
Maximum Reach	800 mm	820 mm
Number of Controlled Axes	7	7
Position Repeatability	±0,1 mm	±0,15 mm
Weight	22 kg	30 kg
Mounting Positions	Ceiling/Floor/Wall	Ceiling/Floor/Wall
Ambient Temperature	5 °C to + 45 °C	5 °C to + 45 °C
Controller	KUKA Sunrise Cabinet	KUKA Sunrise Cabinet
Protection Class	IP 54	IP 54
Protection Class Inline Wrist	IP 54	IP 54

Figure 52: iiwa picture from KUKA

5.3.1.2.2 FANUC

The CR-7iA is small, flexible and can work in any collaborative task. This robotic arm can take care of light (up to 7 kg) but tedious and repetitive, manual tasks that include different types of material handling, which would otherwise consume an immense amount of time. Depending on the need, the CR-7iA can be programmed to perform entire process flows that require steady and reliable quality levels. These tasks can range from small parts assembly to highly repetitive tasks such as picking and placing items from one place to another. The long reach of 911 mm makes this the ideal candidate for machine tending and palletizing applications.

This collaborative robotic arm does not need to be fenced in since it has a proven sensor technology integrate inside, which automatically makes it stop after a collision with a fixed object or any human interaction. This not only saves space, but it also reduces manufacturing costs. It is compatible with existing FANUC accessories like iRVision.

The CR-7iA comes in two different sizes one standard arm and one long arm version and other than that, both are much alike. The benefit of each depends on the needs, as the standard arm is suited better if there are spacing issues, while the long arm can reach further in case the workspace is wider spread.

Table 5: CR-7iA Technical Specifications

System Parameter	CR 7iA
Controlled Axes	6
MaxLoad Capacity at Wrist	7 kg
Repeatability	0.03 mm
Mechanical Weight	53 kg
Reach	717 mm
Motion Range	J1 - 340° J2 - 166° J3 - 373° J4 - 380° J5 - 180° J6 - 720°
Maximum Speed	J1 - 250°/s J2 - 250°/s J3 - 250°/s J4 - 250°/s J5 - 250°/s J6 - 250°/s
Mounting Method	Floor, Upside-down, Wall

Figure 53: CR-7iA picture from FANUC

5.3.1.2.3 UNIVERSAL ROBOTS

The Universal Robots UR10e collaborative industrial robot arm is the largest industrial robot arm produced by Universal Robots, designed for bigger tasks where precision and reliability are still of paramount importance. With the UR10e industrial robot arm is easy to automate processes and tasks that weigh up to 10 kg.

Heavier-weight collaborative processes, such as packaging, palletizing, assembly, and pick and place are all well-suited to the UR10e industrial robot. With a reach radius of up to 1300mm, the UR10e industrial robot is designed to be more effective at tasks across a larger area.

The UR10e collaborative industrial robot is easy to program, offers fast set-up, is collaborative and safe, and like other collaborative robots, offers one of the fastest payback times in the industry.

The UR10 is a robot that has all the right specifications: It's inexpensive, it has the range that not many other cobots have, and it has the payload so it can lift any product needed to lift. And it's quite flexible in its programming.

The exchangeable end-effector is one of the advantages this robotic arm offers. The precise positioning due to the high precision encoders incorporated on each of the joints of the arm gives an option to manage all the end-effectors required.

Table 6: UR10 Technical Specifications

System Parameter	UR10
Degrees of Freedom	6 rotating joints
Payload	10 kg /22 lbs
Repeatability	±0.1 mm / ±0.0039 in (4 mils)
Weight with cable	28.9 kg / 63.7 lbs
Reach	1300 mm / 51.2 in
Motion Range	Base: ± 360° Shoulder: ± 360° Elbow: ± 360° Wrist 1: ± 360° Wrist 2: ± 360° Wrist 3: ± 360°
Maximum Speed	Base: ± 120°/Sec. Shoulder: ± 120°/Sec. Elbow: ± 180°/Sec. Wrist 1: ± 180°/Sec. Wrist 2: ± 180°/Sec. Wrist 3: ± 180°/Sec.
Power Consumption	Min 90W, Typical 250W, Max 500W
Robot Mounting	Any
Ambient Temperature Range	0-50°*

Figure 54: UR10 picture from Universal Robots

5.3.1.3 Sensors

There are several sensors required for the UGV, several will work on the positioning of it in terms of the fault inspection. The localization of the UGV is one of the most important aspects of the RIRS, giving a precise position of a fault will provide a significant advantage for this project. It is vital to give a precision location for the fault and also to give a corrective capacity to the autonomous machine.

Another sensor required for the UGV is a vision type that allows the robot to avoid obstacles and interact with its surroundings. The collision avoidance and collaboration with other workers is a key factor of the RIRS. Taking into consideration that on the possession are people and obstacles, the UGV should be capable to autonomously drive along then and perform the task.

The last type of sensor will be in charge of the stability of the system as this is a factor that has terrible effects on the development of the repairing task. Knowing that the UGV will be on and off-track, it is important to review the stability of the system and ensure that the robot is always in a steady position to continue with the task required.

The combination of all these sensors will be essential for the correct performance of the RIRS, the task will be completed if the obstacles are avoided, the position is correct and the robot is steady to perform the task. The importance of these elements was dictated by the V&V performed before. Those results showed that if the robot has not fulfilled these steps the procedure will fail, having an error in the inspection and will miss the repair of the fault.

5.3.1.3.1 GPS

There are many types of GPS in the market, but for this application an specific type is required. The accuracy in location is a key factor as mentioned before. To accomplish a precise positioning of the RIRS, the GPS will be working in collaboration with a visual recognition that combined allows a better understanding of the positioning.

Talking about the GPS From single-frequency GLIDE to dual-frequency Precise Point Positioning (PPP) and Real Time Kinematic (RTK), the SMART6-L positions the UGV in outstanding precision. The SMART6-L integrates NovAtel's OEM6 receiver and Pinwheel antenna technologies in a single, rugged housing. The software is upgradeable, and the SMART6-L eliminates the need for costly hardware replacement as requirements change while delivering scalable accuracy and performance.

Having a dual-frequency tracking increases position consistency and mitigates ionospheric effects giving reliability to one of the key challenges of the RIRS. The location can be ensured by a robust system and the redundancy in frequency will allow the UGV position to be accurate. In case the redundancy is not enough it can increased position availability with a GLONASS tracking system.

Figure 55: SMART6-L picture from NovAtel

5.3.1.3.2 LIDAR SENSORS

For the awareness of the UGV surroundings it is important to have an idea of how the environment on which the RIRS will be performing the tasks. There are several solutions on the market, from cameras to radars but the importance of interacting with a ROS platform is key in the selection process.

LiDAR sensors have already been in global industrial use for decades. The sensors protect people and enable process flows to be automated. They work both indoors and outdoors. Port automation, traffic management systems, and object protection systems are just some examples of the potential applications for this technology.

Sensors that use lasers to perform non-contact distance measurements have become an integral part of automation engineering. Its development first began in the form of TOF measuring technology. TOF (time-of-flight) has since been largely replaced by the more accurate terms LADAR or, most commonly, LiDAR. The terms LADAR (Laser Detection and Ranging) and LiDAR (Light Detection and Ranging) are, of course, based on the popular term RADAR, which stands for Radio Detection and Ranging.

If the measuring beam is moved or is rotated on one level, this indicates the distance and angle, so the results are in two dimensions. Sensors employed for these kinds of measurements are usually known as 2D laser scanners or 2D

LiDAR sensors. They detect measured values in sequential order, usually at an equal time interval between measurements.

LiDAR sensors operate in the third dimension when they are pivoted. Pivoting provides information about the distance and position along the X-axis as well as positions along the Y and Z-axes. The same information can be obtained about the different space parameters when multiple sender and receiver systems placed at different horizontal angles of a sensor scan while moving. This is now known as a multi-layer scanner.

The LMS111 laser measurement system provides robust indoor/outdoor range readings in a 2D field of view. SICK LMS lasers are rugged, accurate and reliable. They are the best choice for dealing with light interference or poorly reflective surfaces.

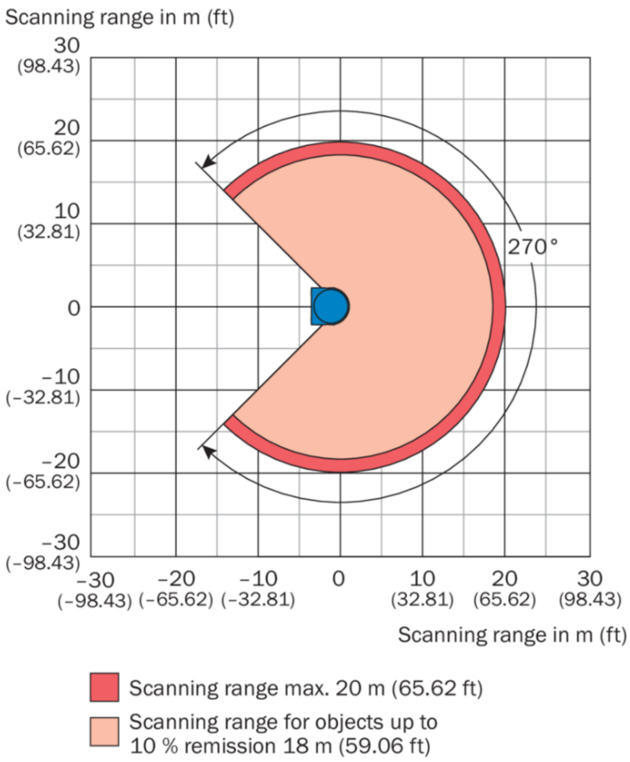

Figure 56: Scanning range for LiDAR LMS111 from SICK

Figure 57: LMS111 LiDAR picture from SICK

5.3.1.3.3 AHRS

An attitude and heading reference system (AHRS) consists of sensors on three axes that provide attitude information, including roll, pitch and yaw. These are sometimes referred to as MARG (Magnetic, Angular Rate, and Gravity) sensors and consist of either solid-state or microelectromechanical systems (MEMS) gyroscopes, accelerometers, and magnetometers.

The 3DM-GX5-25 is the smallest and lightest precision industrial AHRS available. It features a fully calibrated and temperature compensated triaxial accelerometer, gyroscope, and magnetometer to achieve the optimum combination of measurement qualities under all dynamic conditions. The dual on-board processors run an exclusive Auto-Adaptive Extended Kalman Filter (EKF) for outstanding dynamic attitude estimates, making it ideal for a wide range of applications, including platform stabilization, robotics, and vehicle health and usage monitoring.

The following features of this AHRS prove its high capacity to stabilize the orientation of the platform for the mobile unit:

- High-Performance Accelerometer
    - 25 μg/√Hz (8g option)

    - 80 μg/√Hz (20g option)
- Super-stable Gyro
    - 8 DPH in-run bias (-40 to +85°C)
    - Offset temperature hysteresis 0.05°/s
    - ARW 0.3°/√hr
- Pitch-roll static/dynamic accuracy ±0.25°/0.4°High

The MicroStrain 3DM is a high-accuracy attitude heading reference system that utilizes MEMS sensor technology. The sensor combines a triaxial accelerometer, gyro and magnetometer, temperature sensors and on-board processor. Inertial measurement data is typically incorporated into pose calculations to improve localization estimation.

Figure 58: 3DM-GX5-25 picture from LORD

5.3.1.4 Hardware scaling decisions

Having all the information of several industrial products that are robust enough to give the second phase of the RIRS a compact base to be developed, some decisions have to be made. The fundamental one is to define the mobile unit where all the platforms will be established. Knowing that each one of the mobile units from CLEARPATH ROBOTICS is almost the same and that the difference between them is the size; two main mobile units stand out the HUSKY and the

WARTHOG both can perform in similar ways. The major difference is that the WARTHOG is capable to operate underwater, taking in consideration that some of the CES is located near a river or a lake it can be helpful that the mobile unit don't be restricted by any weather or water on the location of the possessions,

Once the mobile unit was selected the following element to consider is the robotic arm, this system should be capable to operate on top of the mobile unit underlining that the working area of the robot should be bigger than the mobile unit platform and can reach the rail to perform the inspection and repair process. Having this in mind, it is important to select a robot compatible with the operating system ROS and able to perform the activities on the mobile unit.

Universal Robots meet all the requirements and having the possibility to adapt different end-effectors will make the UR10 the ideal robotic arm to work with. Also its 1300mm reach range allows the atm to perform any activity required.

The sensing scalability and selection was straight forward as the mobile unit was selected CLEARPATH ROBOTICS offers a wide range of sensors compatible with the platform, also they help with the integration of all the systems together for plug and play unpacking. This brings significant help in terms of efficiency and time management.

5.3.2 Software scaling

The control side of the RIRS has to be a priority scale system as the current control of the physical demonstrator is made by out of the shelf materials, like Arduino and Raspberry Pi, these elements are not industrial sized and don't meet the TRL criteria for industrial implementation. The importance of having a robust system that controls the RIRS generates the need of new control implementation.

The type of industrial controllers that are currently available are robust enough to incorporate to the RIRS but the main challenge is to combine the top new technologies to this system.

The usage of high-performance controllers like PLC is the most common, PLCs can range from small modular devices with tens of inputs and outputs (I/O), in a housing integral with the processor, to large rack-mounted modular devices with a count of thousands of I/O, and which are often networked to other PLC and SCADA systems.

They can be designed for many arrangements of digital and analog I/O, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact. Programs to control machine operation are typically stored in battery-backed-up or non-volatile memory.

Even if PLC is a well-known control element the ideal is to have a higher technology level, this includes new areas of technologies such as ROS. Exploring these controllers was part of the scope of this thesis. Also, the new technologies developed recently have better combinations and faster performance.

5.3.2.1 ROS

Robot Operating System (ROS) is a robotics middleware. Although ROS is not an operating system, it provides services designed for a heterogeneous computer cluster such as hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management. Running sets of ROS-based processes are represented in a graph architecture where processing takes place in nodes that may receive, post and multiplex sensor data, control, state, planning, actuator, and other messages. Despite the importance of reactivity and low latency in robot control, ROS itself is not a real-time OS (RTOS). It is possible, however, to integrate ROS with real-time code. The lack of support for real-time systems has been addressed in the creation of ROS 2.0, a major revision of the ROS API which will take advantage of modern libraries and technologies for core ROS functionality and add support for real-time code and embedded hardware.

The software in the ROS Ecosystem can be separated into three groups:

- Language-and platform-independent tools used for building and distributing ROS-based software;
- ROS client library implementations such as roscpp, rospy, and roslisp

- packages containing application-related code that uses one or more ROS client libraries.

Both the language-independent tools and the main client libraries (C++, Python, and Lisp) are released under the terms of the BSD license, and as such are open source software and free for both commercial and research use. The majority of other packages are licensed under a variety of open-source licenses. These other packages implement commonly used functionality and applications such as hardware drivers, robot models, datatypes, planning, perception, simultaneous localization and mapping, simulation tools, and other algorithms.

The main ROS client libraries are geared toward a Unix-like system, primarily because of their dependence on large collections of open-source software dependencies. For these client libraries, Ubuntu Linux is listed as "Supported" while other variants such as Fedora Linux, macOS, and Microsoft Windows are designated "experimental" and are supported by the community. The native Java ROS client library, rosjava, however, does not share these limitations and has enabled ROS-based software to be written for the Android OS. rosjava has also enabled ROS to be integrated into an officially supported MATLAB toolbox which can be used on Linux, macOS, and Microsoft Windows. A JavaScript client library, roslibjs has also been developed which enables integration of software into a ROS system via any standards-compliant web browser.

ROS processes are represented as nodes in a graph structure, connected by edges called topics. ROS nodes can pass messages to one another through topics, make service calls to other nodes, provide a service for other nodes, or set or retrieve shared data from a communal database called the parameter server. A process called the ROS Master makes all of this possible by registering nodes to itself, setting up node-to-node communication for topics, and controlling parameter server updates. Messages and service calls do not pass through the master, rather the master sets up peer-to-peer communication between all node processes after they register themselves with the master. This decentralized architecture lends itself well to robots, which often consist of a subset of networked computer hardware, and may communicate with off-board computers for heavy computation or commands.

5.3.2.2 Operational phases

The phases of operation for the scales concept demonstrator (RIRS) as identified in the requirement definition process are listed in Table 7

Table 7: Phases of operation as identified in the stakeholder requirement definition process

Ref	Parent Requirement	Name	Requirement
		Pre-mission phase	
01	**Mission Phase**	Select Job	The System shall have a “Select Job” operation to select from a job from the live worklist, based on current system and consumables status as well as time constraints.
02	**Mission Phase**	Transit to Job Operation	The System shall have a “Transit to Job” operation where the RIRS positions in the appropriate section.
03	**Mission Phase**	Task Positioning	The System shall have a “Task positioning” operation where elements of the payload module are positioned to be able to carry out the job.
04	**Mission Phase**	Execute Task	The System shall have an “Execute Task“ operation where the payload module executes the task.
05	**Mission Phase**	Recovery to Base	The System shall have a “recovery to facility” operation whereby the RIRS repositions at the designated base.

Post-mission phase

The sequence of operation from one phase to the next under normal operating conditions is shown in Figure 56. A pre-mission phase is the starting point of any operation and in this phase the vehicle and required payload modules are prepared for operation. When readiness for the mission is confirmed, a job is selected from the current worklist that can be completed with the current RIRS status. Following this the transit to the job phase is entered, where the vehicle will navigate to the current job location. On confirmation that the job location has been reached the job position phase will be entered where the vehicle will position itself more precisely to allow the repair job to be undertaken. When confirmed in position the repair job is executed and inspected to confirm it has been completed satisfactorily. If this is not the case, the job position phase will be re-entered to attempt the job again, if possible, otherwise on satisfactory completion of the job the next job from the worklist will be selected. On completion of all jobs in the worklist or on insufficient power or consumables to complete any further jobs the recovery to base phase will be entered, where the RIRS-CD will return to the location designated as its base for the given mission. When the RIRS-CD has been confirmed to have returned to base the post-mission phase is entered where the RIRS-CD is inspected, maintained and returned to a neutral state in preparation for the next pre-mission phase. Further details of each phase are given in the following sections.

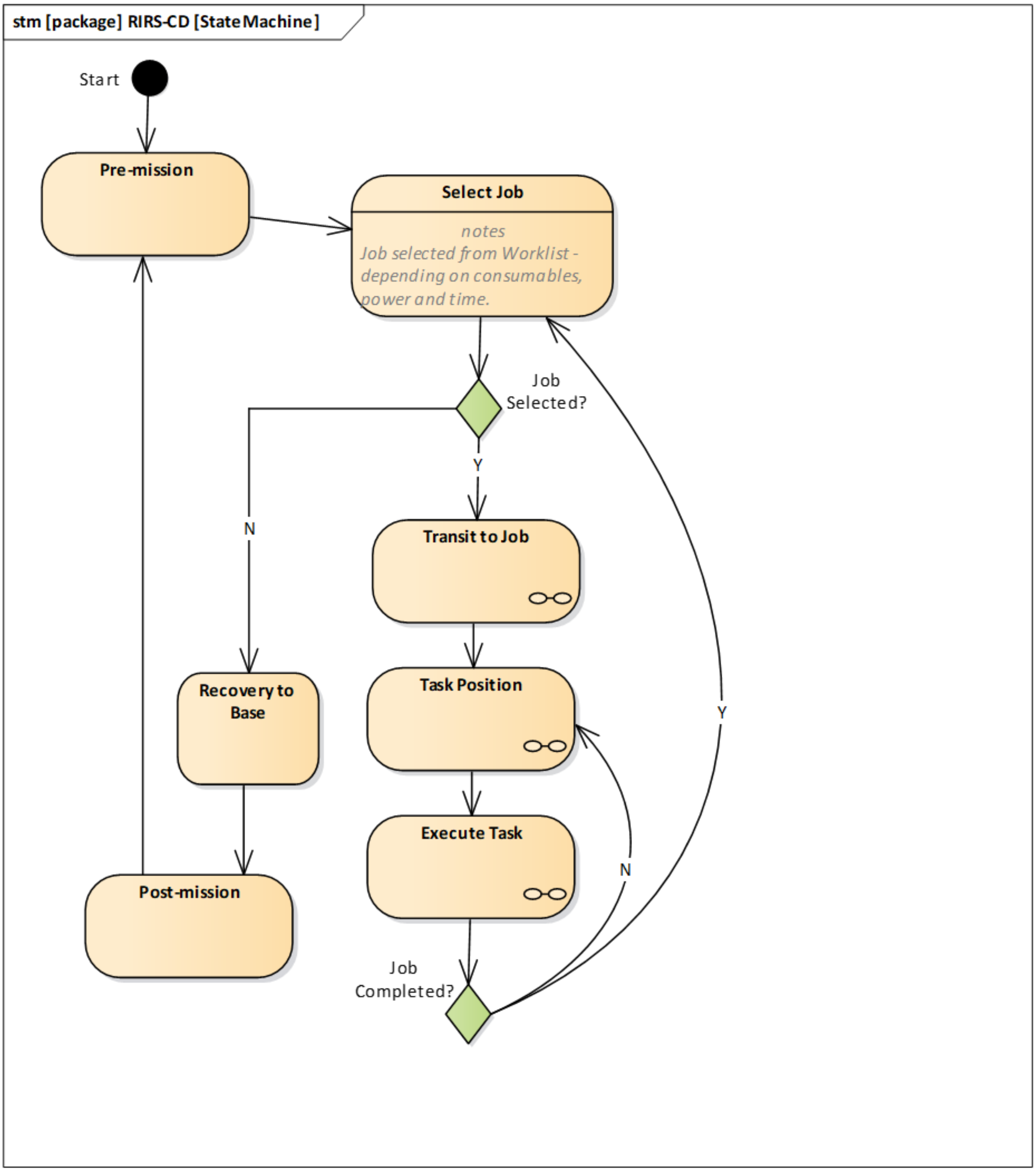

Figure 59: Concept Demonstrator State Machine Diagram

5.3.2.2.1 Pre-mission

Before the mission taking place it is necessary to ensure that the RIRS is sufficiently replenished and the required modules are fitted and operational to undertake the jobs required for the upcoming missions. This work is done manually by maintenance personnel with vehicle status provided at the operator interface.

5.3.2.2.2 Select Job

A list of jobs to be undertaken is made available to the RIRS in the format received from Ellipse and a decision is made as to which job to undertake based on the requirements of the job and the available time, on-board power and consumables. The worklist, selected job and system status are available on the operator interface.

If jobs are available and there are sufficient materials, time and power then the next suitable job is selected and the transit to the job phase is entered, otherwise, the recovery to base phase will begin.

5.3.2.2.3 Transit to Job

The transit to the job phase dictates the movement of the RIRS from its current rail position to the current job location under operator supervision. The operator supervision can be undertaken remotely, however, for testing, it may be desirable to have the operator or observers on site. A flow diagram of the phase is shown in Figure 60.

On receipt of a job location, this phase begins with operator approval to proceed with locating the vehicle and planning its motion to the job location. The operator interface is used to approve. By combining the data from the position sensors with prior information about the vehicle, its location can be estimated within a model of the environment. With the current job location as a destination and the estimated position as a starting point the path required to reach the destination is calculated. The planned motion is presented to the operator via the operator interface and if approved the motion plan is implemented by the vehicle motion control module with manual control by the operator. In parallel to this activity, the environment local to the vehicle is monitored and appropriate action is taken to ensure the safety of the vehicle and its surroundings as well as the provision of a stop command on the operator interface that provides the base to the operator to stop the vehicle at any time. The progress of the vehicle against the planned path is presented via the operator interface in real-time along with living information from the vehicle. During transit, any moveable parts of the vehicle or payload are to be stowed and disabled to prevent violation of the loading gauge constraints, both static and dynamic. The payload status is monitored to ensure that it is in a safe state to travel.

On reaching the destination, the vehicle is stopped by the operator who confirms the location indicated by the navigation system corresponds with the defect location. Following this the phase is considered completed.

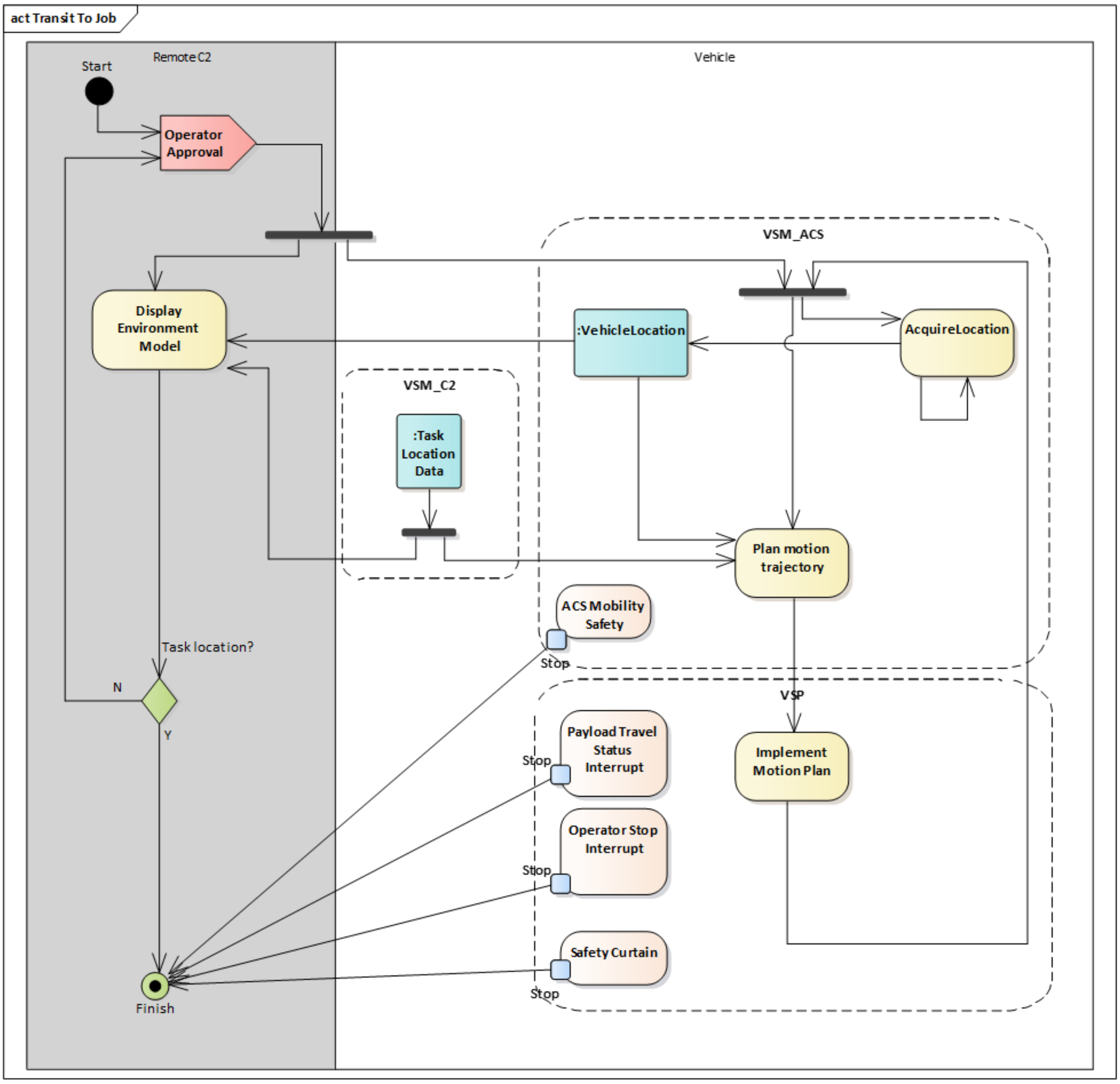

Figure 60: Transit to job phase flow diagram

5.3.2.2.4 Task Position

When the RIRS has reached the location described by the job information, the position of the defect needs to be confirmed before the tasks being executed. Upon entering the job position phase, the railhead inspection module is deployed to detect the defect and when sufficient contact between the rail and measurement system is confirmed the RIRS moves at reduced speed along the length of the area of interest to establish the depth and then the length of the defect. Scanning while traveling at this reduced speed occurs until the measurement data corresponds to the defect under investigation. This data is then used to classify the severity of the defect according to the designated standard.

Following identification and classification, a report is sent to the Rail Defect Management System (RDMS) and a decision is made by the operator to either begin the defect repair process or if the repair is not to be undertaken this outcome is also reported to the RDMS.

When the defect position is confirmed the RIRS moves to the correct position for the task to be executed by the payload module. while the RIRS remains stationary.

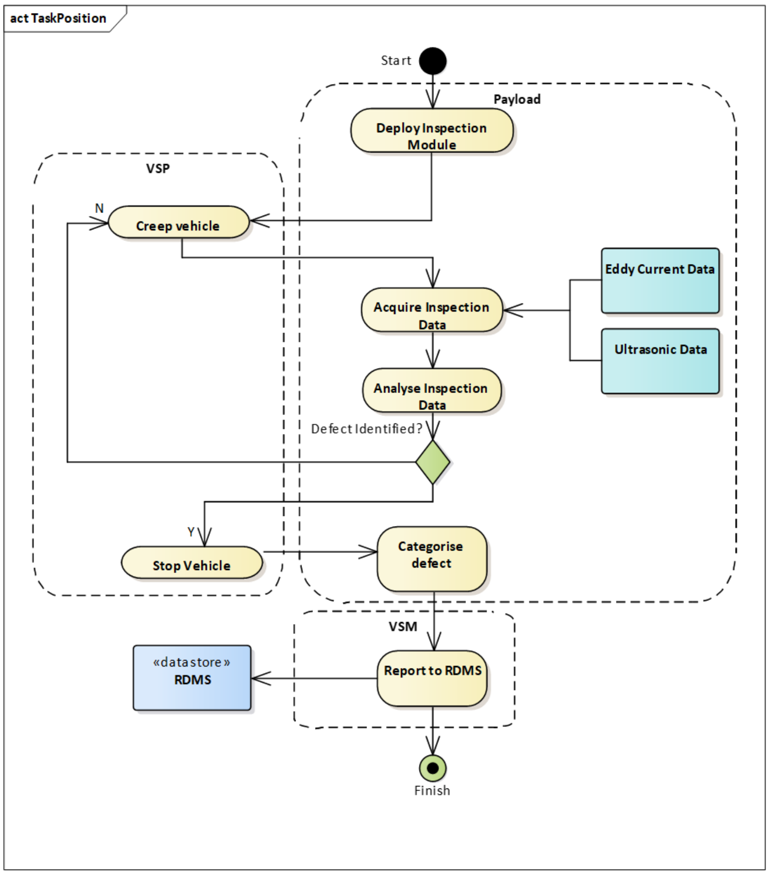

Figure 61: Activity Diagram of Task Position phase

5.3.2.2.5 Execute Task

When the RIRS has reached the current job location, the fault has been detected and the RIRS has positioned itself accordingly the repair task can be executed. Due to variation in the rail local environment operator input is required to ensure that the repair operation does not require additional operations such as removal of fishplate or protection of electrical infrastructure items.

If the repair is to take place then the vehicle needs to reposition itself so that the defect removal operation can commence. When the defect removal start position is confirmed the operation begins and on completion the work is to be inspected to confirm the defect is removed. If this is not the case the milling start position is returned to and the process repeated. On confirmation that the milling was inspected satisfactorily the welding position is requested and on position confirmation the welding operation takes place. On completion, the depth of the newly welded rail is measured and if it is less than required then the welding process is repeated accordingly, if it is more than required then a grinding process is undertaken and if it is as required then the welding process is complete.

On confirmation of the weld process completion, the railhead is scanned and the blend profile is calculated to ensure a smooth transition before and after the repair. The grinding equipment is deployed, the calculated blend profile is ground and on completion a rail inspection is undertaken to confirm the defect is repaired.

Following a satisfactory inspection the RDMS report is sent, otherwise, the defect repair process is repeated at the request of the operator via the operator interface and the system returns to the job position phase. The status of the vehicle consumables is regularly updated to account for the amounts used in the execution of the job.

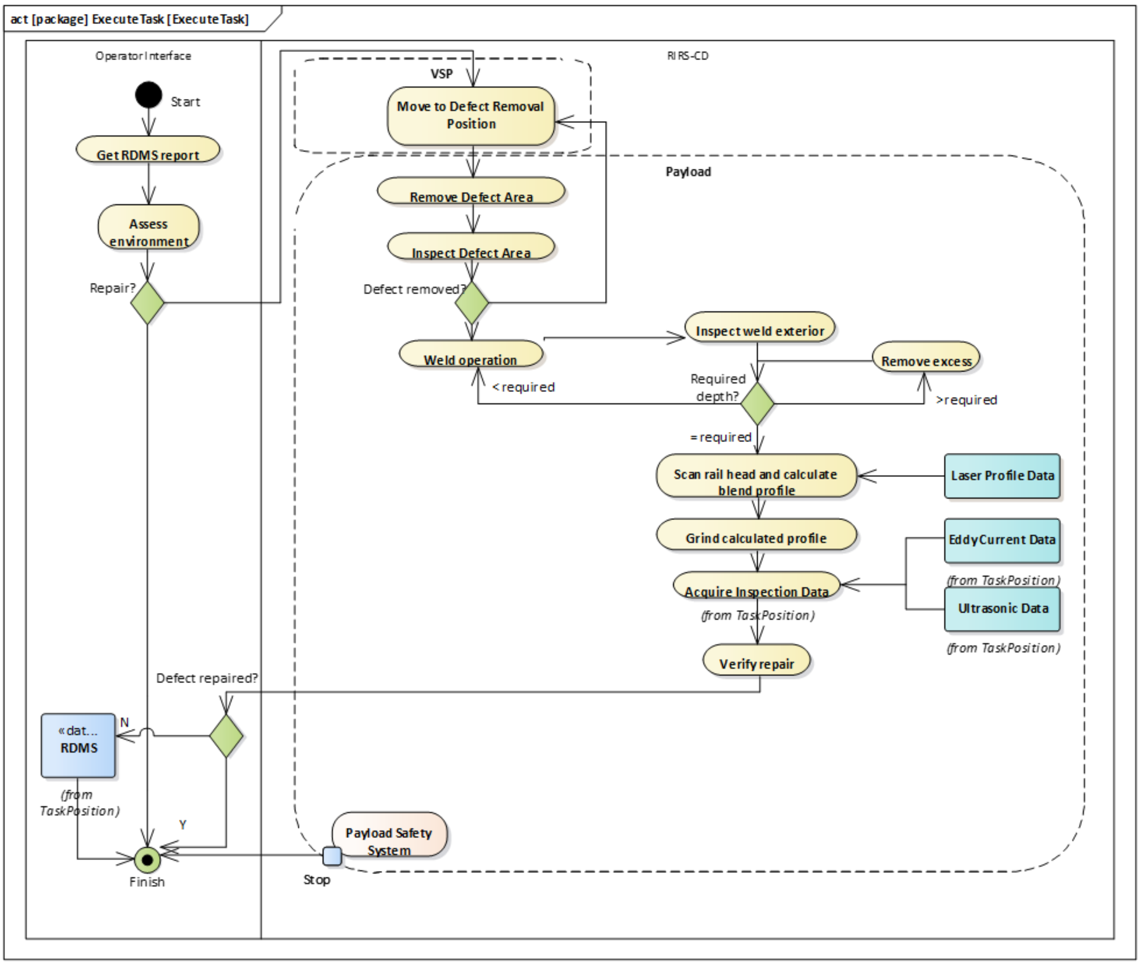

Figure 62: Activity Diagram of Execute Task phase

5.3.2.2.6 Recovery to Base

On completion of the current worklist, an inability to complete the worklist jobs or when otherwise requested by either the operator or by an automated decision, the RIRS is to return to a given location to be prepared for standby, awaiting the next mission.

The RIRS operating status will be updated on the operator interface to indicate that the recovery to the base phase has been instigated. To return, the RIRS will use its current location and the base location to plan a path and navigate a safe return. The progress of the recovery to the base phase will be indicated on the operator interface until completion. The commonality between this phase and the travel to the job phase will be exploited.

5.3.2.2.7 Post-mission

The RIRS, on returning to the storage facility, is required to be assessed and replenished to be available for future operations. This operation is undertaken manually by maintenance personnel assigned to the testing process.

5.3.2.3 Functional model

The functions of the RIRS are detailed in Figure 63 with functions decomposed to allow further examination. The RIRS functions are initially decomposed into functions associated with the vehicle system and those associated with the remote command and control system.

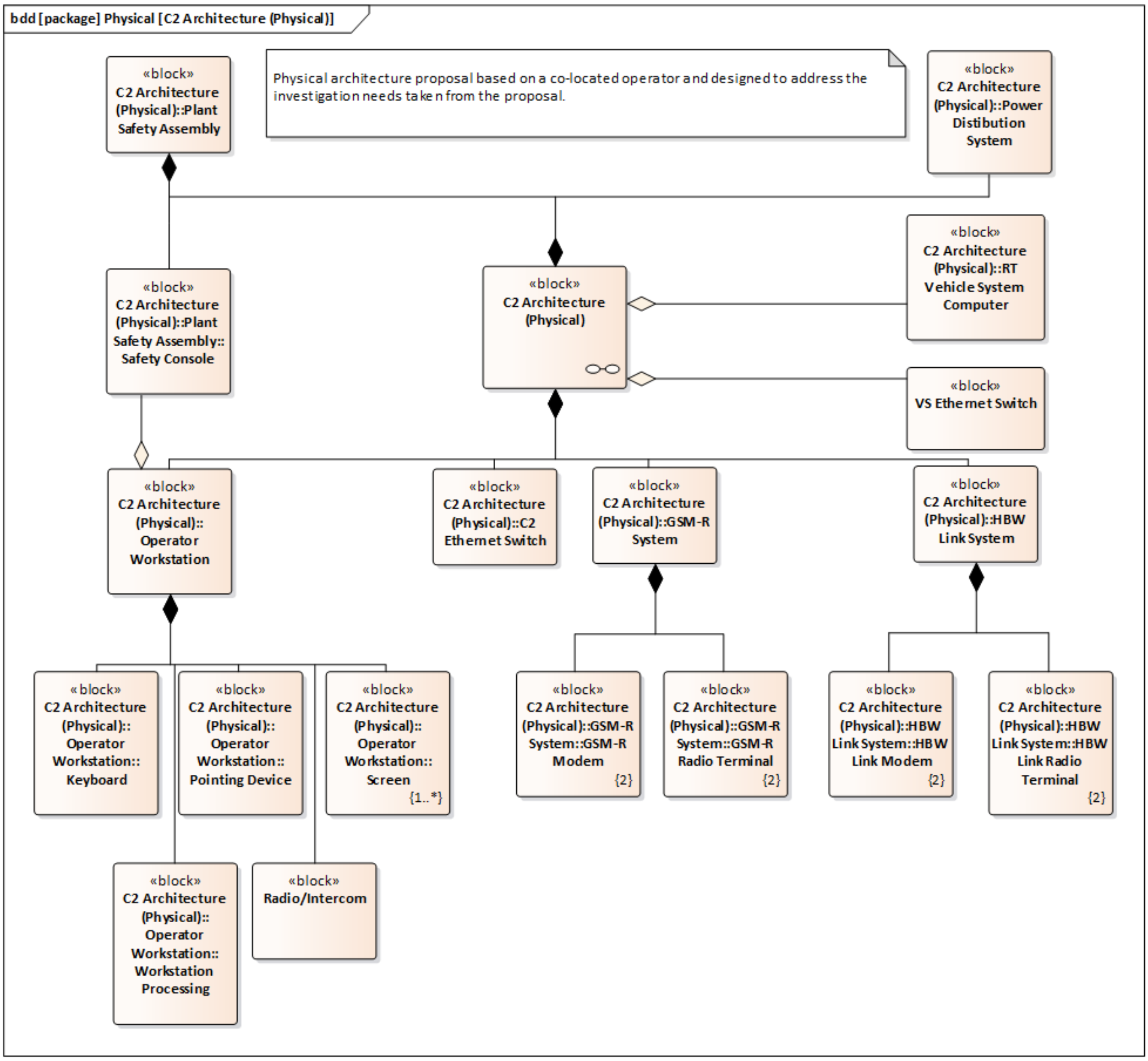

Figure 63: Functional Model for RIRS

The RIRS vehicle system functions are composed of the vehicle system manager functions related to communication, power and navigation, the vehicle platform sub-system as well as payload sub-system functions related to the payload deployed. The Vehicle Systems Manager (VSM) sub-system is examined in further detail in Figure 64.

The VSM is composed of: -

- VSM Communication
- VSM Monitoring Module (VSM_MON)

- VSM Power Module (VSM_PM)
- VSM Command and Control (VSM_C2)
- VSM European Train Control System (ETCS)

The VSM communicates with the remotely located operator via a non-rail specific communication network for concept demonstration. The VSM_V2I provides the interface between the RIRS and the Remote C2 system. The VSM_C2 functional block provides the onboard command and control system capable of high-level decision making such as job prioritizing, destination adjustment and vehicle power and consumable use. The VSM_MON accesses all the information from the numerous functional blocks and provides it for data logging. The VSM_PM functional block monitors and controls power for the VSM functions. The VSM_ETCS module provides a link between the vehicle and the infrastructure of the ETCS systems to receive movement authority from the Radio Block Centre.

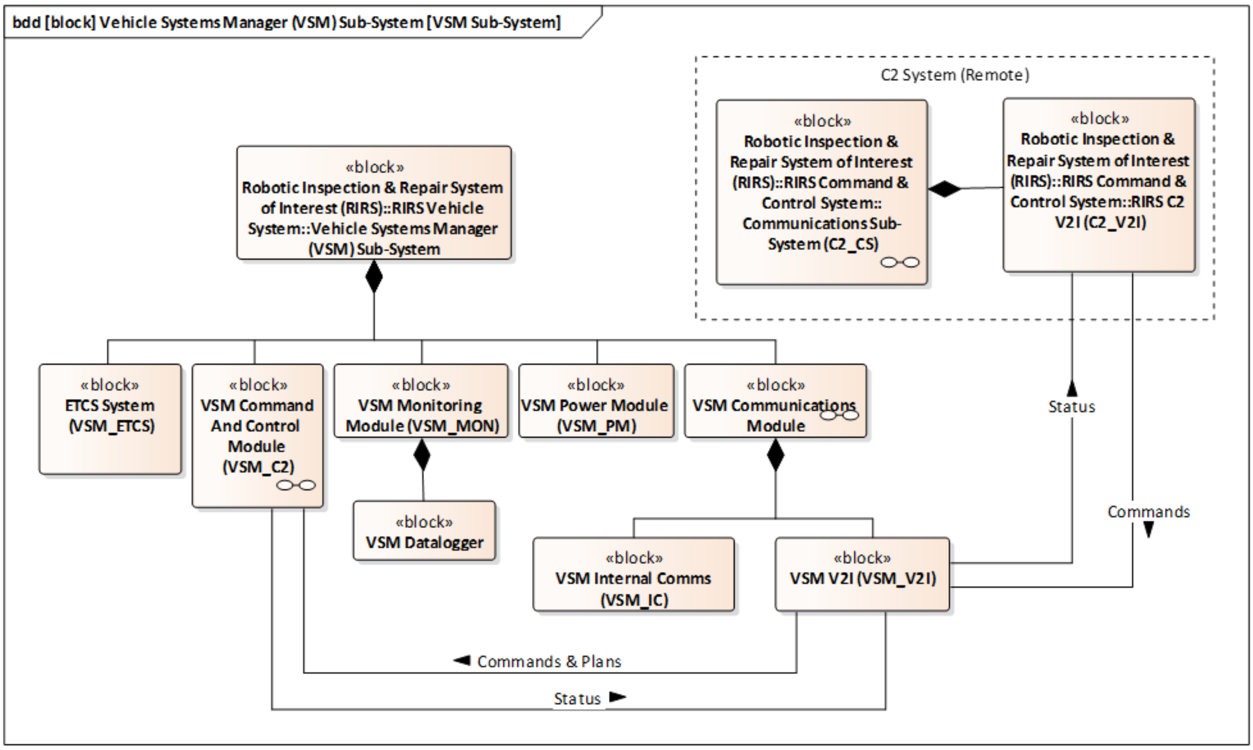

Figure 64: VSM sub-system decomposition modules

5.3.2.3.1 Vehicle System Platform

The VS Platform subsystem is decomposed into functions as seen in Figure 65 comprising of the Base Vehicle and Vehicle System Platform Controller Area Network Interface (VSP_CAN), Autonomous Control System (VSP_ACS), Safety Curtain (VSP_SC), Watchdog (VSP_WAT) and Communications (VSP_COM). There are flow elements across the functional hierarchy to highlight that there should be information flowing between sub-functions, for example, the safety curtain will have an interface to the Vehicle via the Vehicle Controller Area Network (CAN) interface.

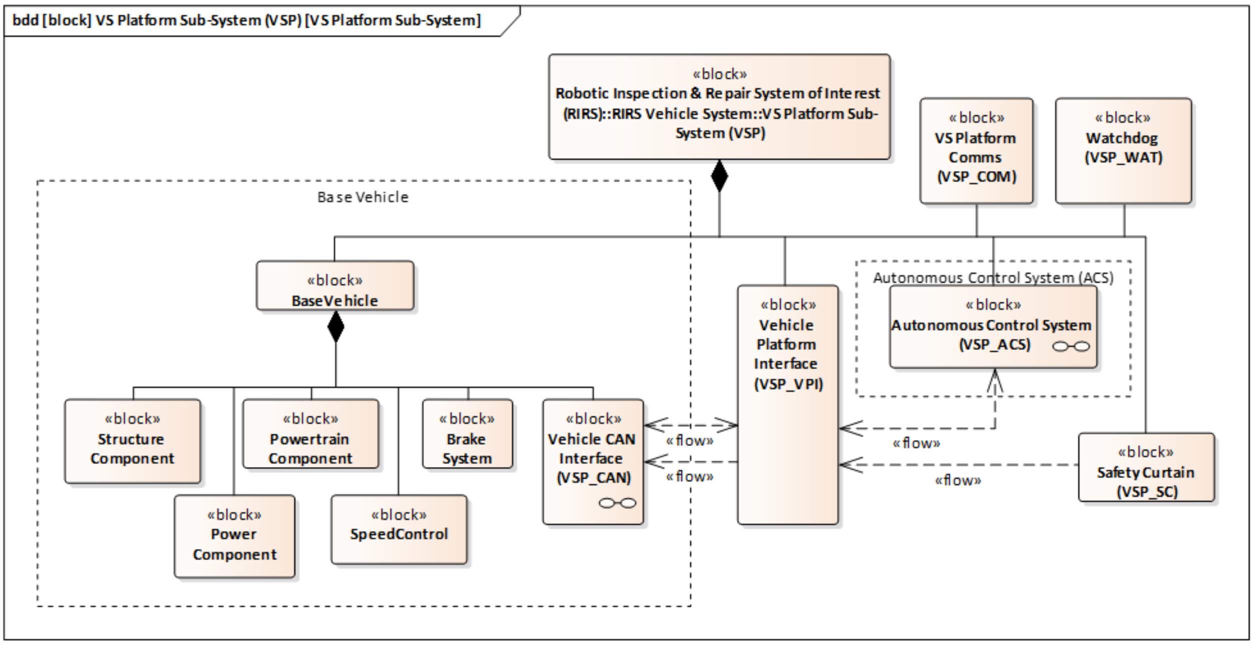

Figure 65: Functional decomposition of VS Platform modules

The Vehicle CAN interface (VSP_CAN) provides access to the vehicle Controller Area Network (CAN) bus which allows data to be sent and received to interact with and control vehicle functions. The VSP_ACS provides the sensing and intelligence to control a vehicle ensuring it reaches a given destination without operator intervention required. The Vehicle Platform Model (VSP_VSM) takes VSP_ACS commands and data requirements and converts them to suit the current vehicle platform being used. This allows the modification of vehicle components,components or even the complete replacement of a vehicle model without requiring exhaustive rework of the VSP_ACS, leading to a modular, flexible system.

The Safety Curtain (VSP_SC) provides a redundant collision avoidance system in addition to the functionality of the VSP_ACS.

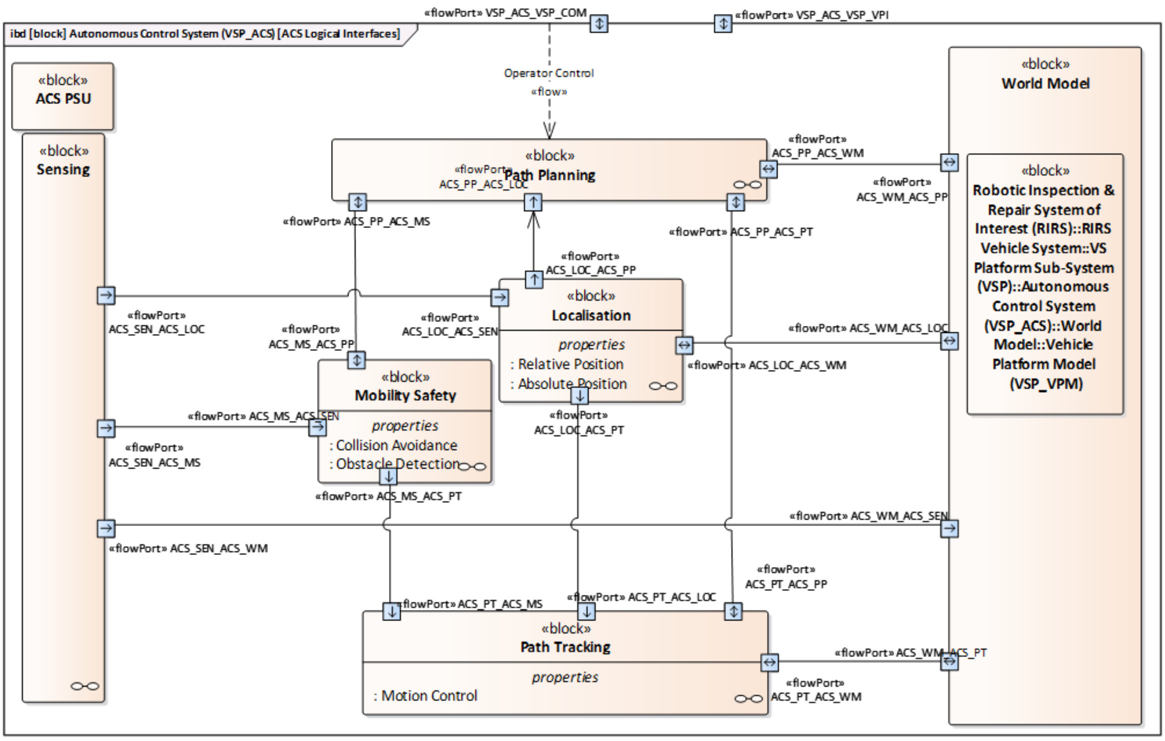

Figure 66: Functional Model for Autonomous Control System (VSP_ACS)

The VSP_ACS comprises the functions shown in Figure 66 with the architecture. The World Model contains information about the environment external to the RIRS that can be static and dynamic. Other VSP_ACS functions can access the World Model to send and receive information about the environment.

The Sensing function contains the information provided by the array of sensors shown in Figure 67 and ensures that the relevant information is available to the functions requiring such information. The highest level in the functional hierarchy of the VSP_ACS is the Path Planning functional block which takes destination inputs and calculates the control trajectory required to safely and efficiently reach the destination from the current location. The current location is calculated by the localization functional block which takes information from the Sensing block.

The Mobility Safety functional block uses information from the Sensing block as well as the Path Planning block to ensure that the planned path avoids collisions and adjusts the path current control trajectory if required.

The Path Tracking functional block is responsible for implementing the path provided by the Path Planning block while also reacting to the input from the Mobility Safety block if required. The Path Tracking functional block provides commands to the VSP_VSM to transform into vehicle-specific commands.

An alternative to the Vehicle Platform Model (VSP_VPM) residing separately from the ACS is for the vehicle-specific characteristics to be a module of the world model which can be interchanged when changes or replacement occurs with the RIRS.

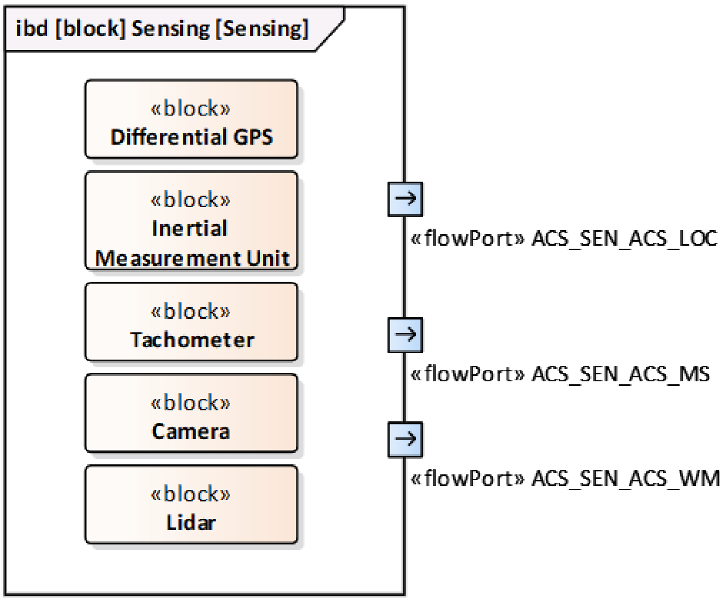

Figure 67: Internal block diagram for sensing functional block

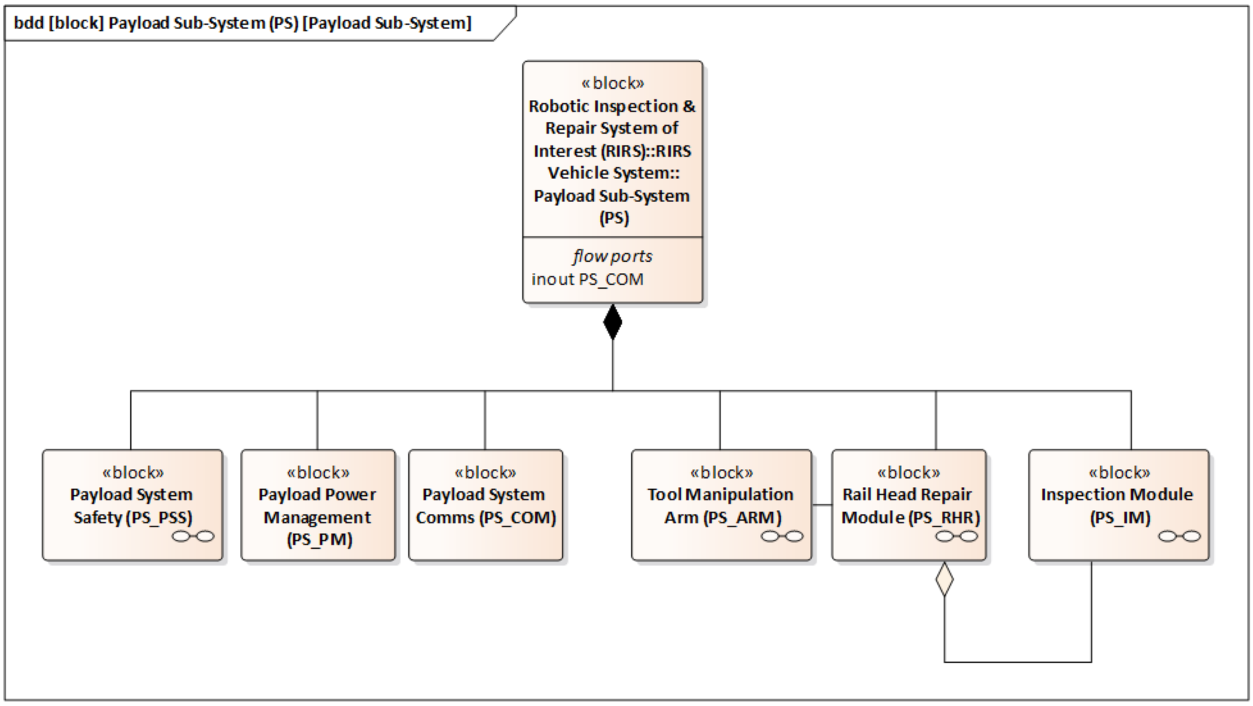

Figure 68: Functional Model for Payload sub-system

The payload sub-system is functionally decomposed into the following: -

- Payload System Safety (PS_PSS) – ensuring that the payload is safe and secure for travel as well as during payload operation.
- Payload Power Management (PS_PM) – to supply, monitor and control the payload power
- Payload Communication (PS_COM) – to provide an interface from the payload to the other system components both internal and external to the Payload sub-system.
- Inspection Module (PS_IM) – to provide and interface to the inspection equipment used to identify the location and condition of a defect and repaired rail.
- Rail Head Repair (PS_RHR) – to deposit suitable material to reform the rail head profile.
- Potential future payload modules (for example Tunnel Inspection Module, Rail End Resin Repair, Change Rail)

5.3.2.3.2 Payload Arm

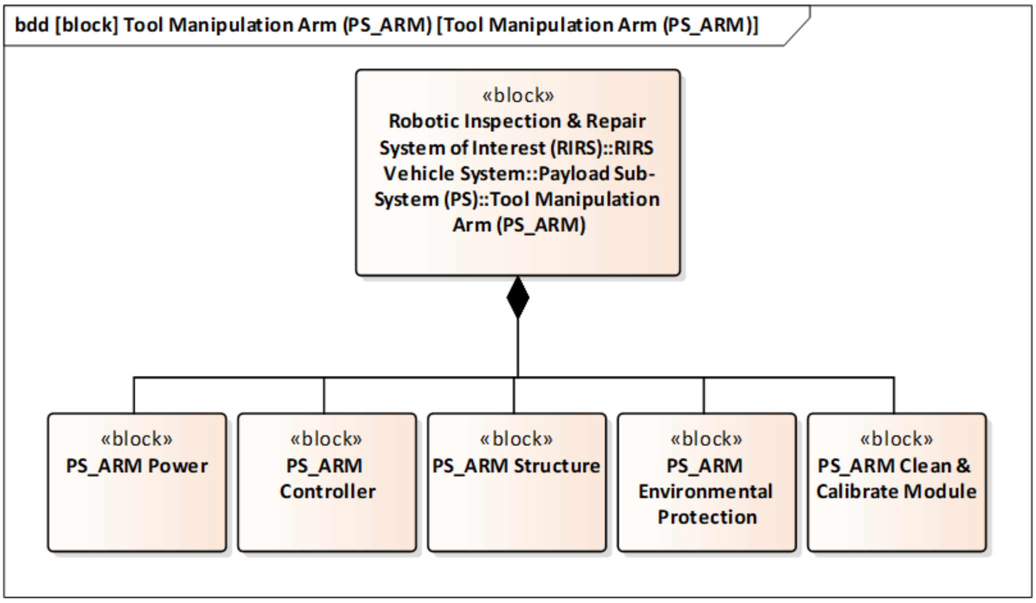

Figure 69: Functional Model for Payload Arm

5.3.2.3.3 Remote Stop System (RSTOP)

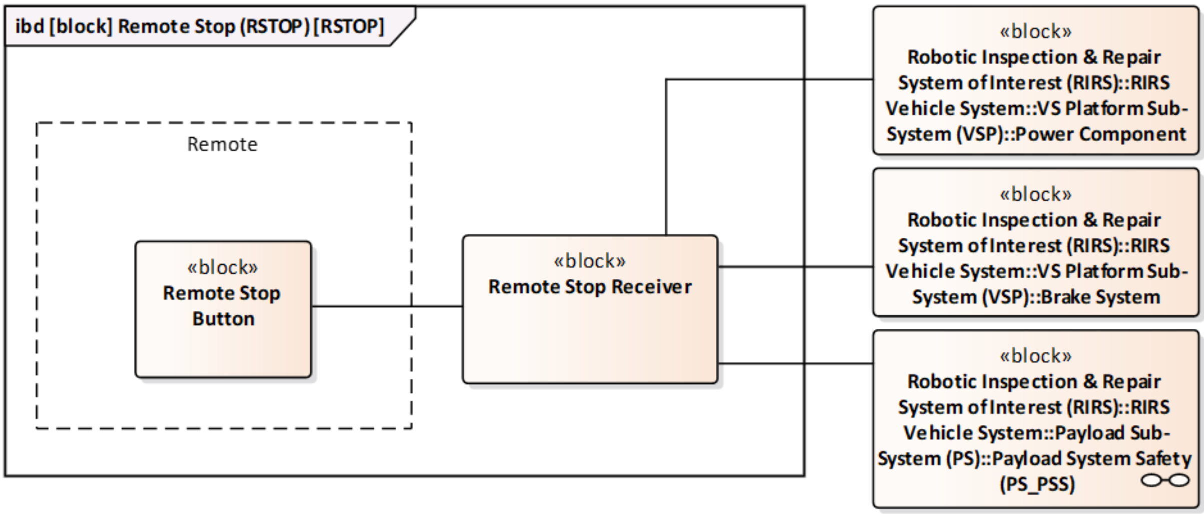

Figure 70: Functional Model for Remote Stop System

The remote stop system includes an onboard remote stop receiver and a remotely located stop button. The remote stop receiver interacts with the VSP power component and brake system as well as the payload safety system to ensure that when the remote stop button is pressed the vehicle and payload enter a controlled state.

5.3.2.3.4 Command and Control (C2) System

The command and control system functional and logical models are detailed in Figure 71 and Figure 72, respectively.

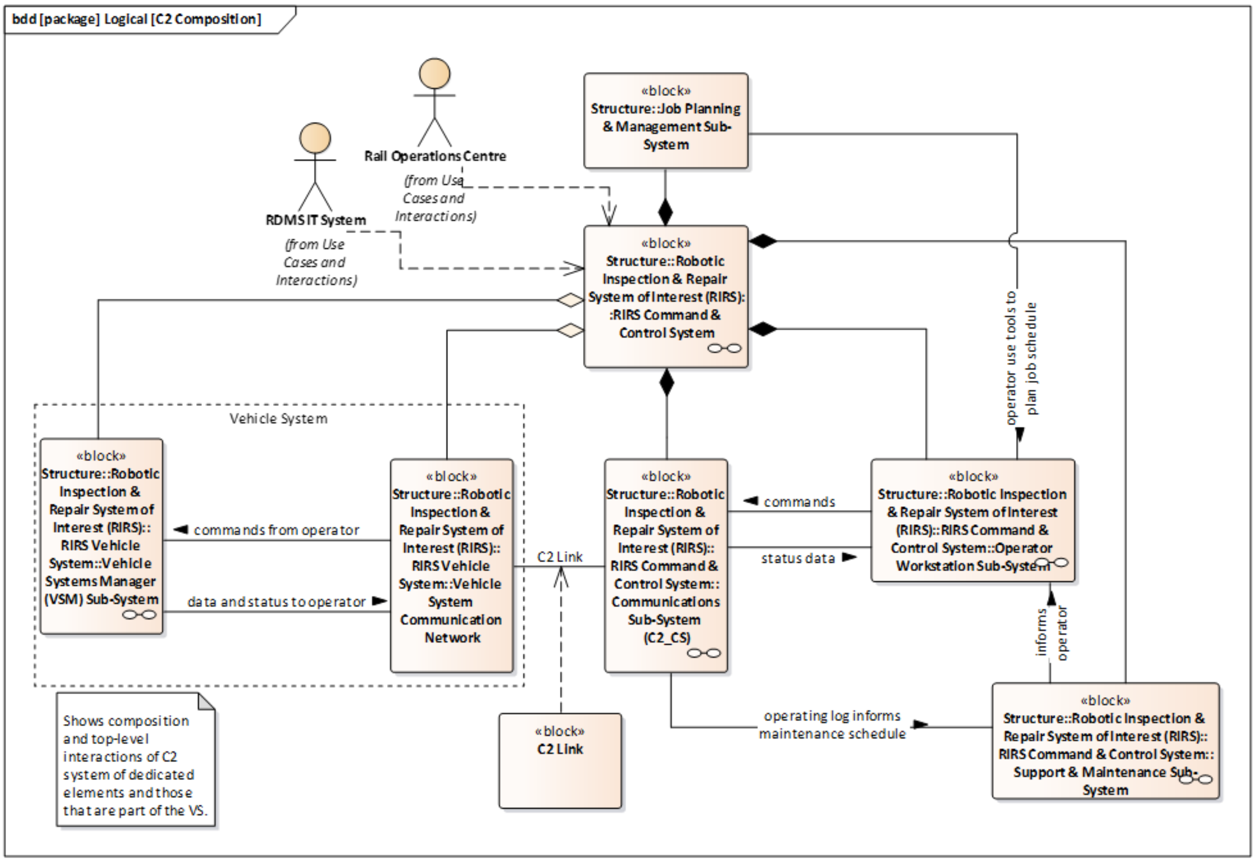

Figure 71: Functional Model for Command and Control System

The C2 system is made up of an Operator workstation, a communication sub-system, support, and maintenance system and Job planning and management sub-system.

This logical relationship between the operator workstation and the communication subsystem is shown in Figure 72. Sub-systems within the operator workstation are the Workstation message manager, the ROC voice link, and user interfaces for the following:

- Operational Picture

- Communication
- Planning
- Monitoring
- Vehicle System Control
- Payload
- Safety Interlocks.

The communication sub-system includes interfaces to the RDMS and asset management systems, the wireless communication network and High BandWidth links as well as the Rail Operating Centre (ROC) for operational authority. The communication manager module provides relevant information from the communication subsystem to the operator workstation message manager.

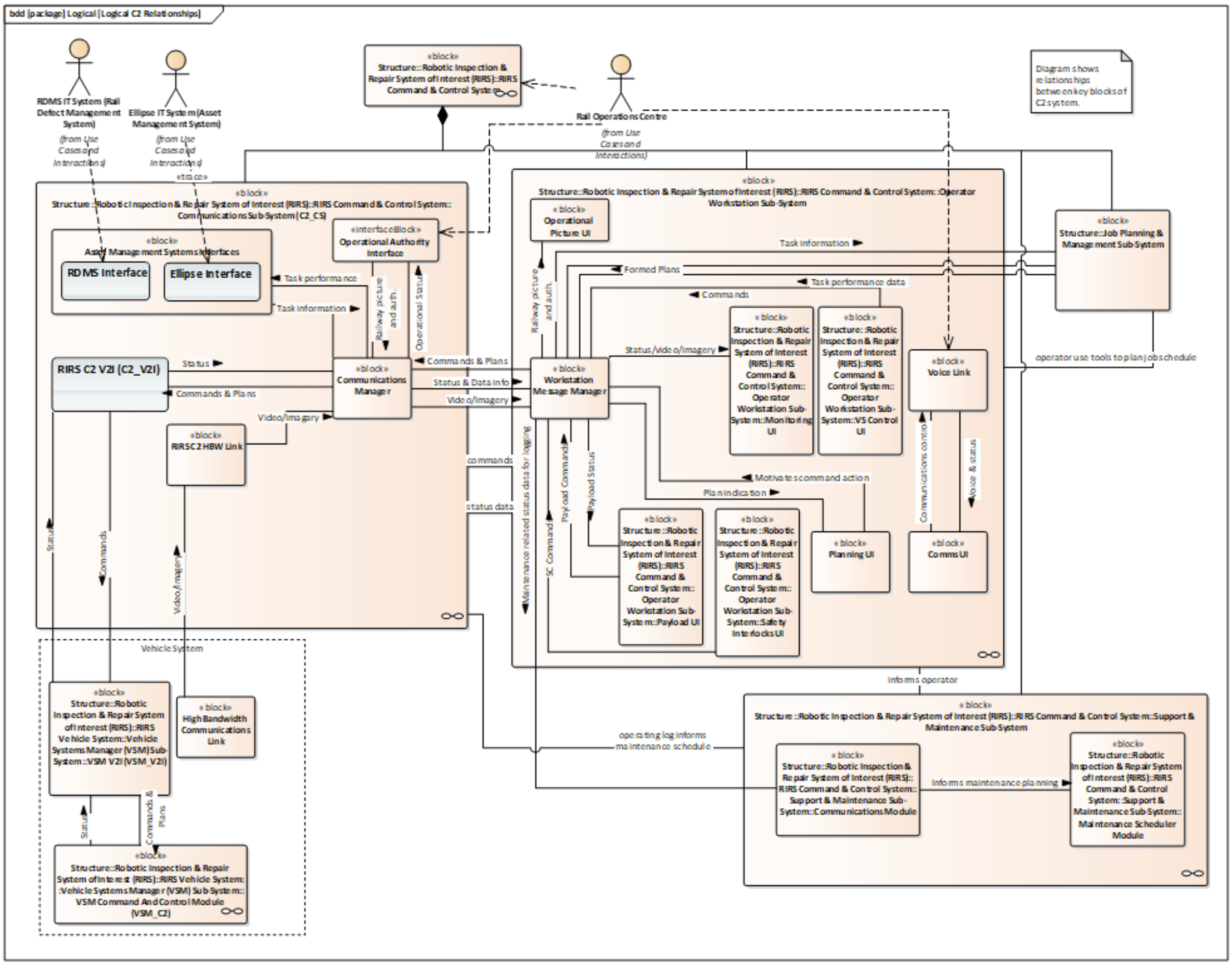

Figure 72: Logical Model for Command and Control System

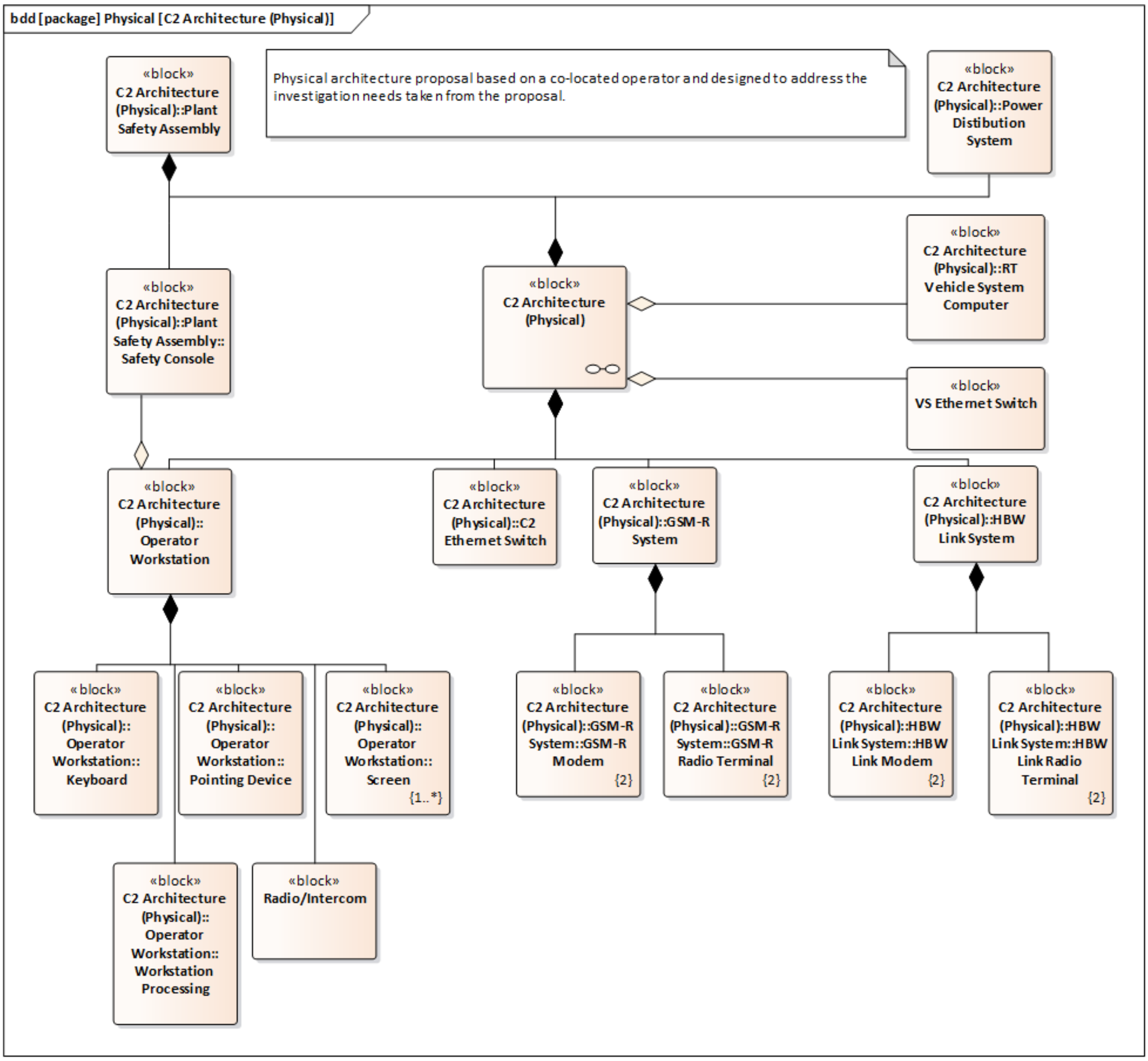

Figure 73: Physical Model for Command and Control System

5.3.2.4 Software scaling decisions

It is crucial to implement this architecture and operational phases to a ROS environment, the coding, and installation of the software is essential for the correct functioning of the system in general.

The implementation of ROS as its control framework facilitates the interaction of software and hardware, achieving a level of robustness ideal for the industry.

Besides all obstacles the testing phase for the software and the CCS is vital for the good performance of the RIRS, taking time to perform the tests required to ensure the positive impact of the control system using ROS.

5.4 Scaled concept description

Having the software and hardware scaled into industry sized elements, capable of the assure robustness to the RIRS. The planning, design, build and testing of the concept demonstrator RIRS will impact Infrastructure Managers across several departments and roles as well as suppliers and contractors. To ensure that adequate preparation is undertaken, an analysis of the impact of each RIRS is required.

The RIRS prototype is intended to be tested on the rail network, the impact during development will extend to involve input from the relevant personnel at the Infrastructure Manager responsible for operations, maintenance, safety, asset management as well as interactions with the network signaling both fixed and moving block.

The RIRS prototype testing will impact the existing rail repair operations if on-network defects are required to be repaired by the RIRS prototype and the co-existence of the two systems has to be considered.

5.4.1 Limitations

Unfortunately due to time limitations the concept proposed on this thesis couldn't be tested as the mobile unite arrived almost at the end of the timeframe given for the presentation of this document. The extent of the research was only until the assembly and initial interaction of the hardware but the software couldn't be fully tested.

To verify and validate the scaled RIRS concept, the stakeholder and system requirements must be evaluated to ensure that they are testable and can be traced from a stakeholder to a stakeholder requirement to a system requirement and vice versa. An assessment is necessary for each requirement criticality, to ensure that priority and depth of testing can be assigned to each requirement.

For system requirements, a similar traceability check is required and each documented test procedure should be traced to one or more system requirements.

The architectural design is to be assessed to ensure that it satisfies the user and system requirements, is realizable, the selection criteria and decision process are clearly documented and interactions with the operating environment will be as intended.

This document can be used for the following phases of the RIRS and is the base of the new concept acquire by Cranfield University and Network Rail, been the precursor of the following plan for IN2SMART2.

6 Discussion

This research is divided into three major elements beginning with the conclusion of the physical demonstrator of the RIRS. The specifications and requirements were previously established, making the main challenge to incorporate all the separate elements Cranfield and Network Rails procured.

The main objective of completing the creation of the demonstrator was achieved and the challenge of developing a main control adaptable to any input was a major contribution to this project. Having a plug and play control system allows any devices that inspects the rail searching for fault can be incorporated easily as well as any repairing mechanism. This makes the project interesting for the industry and creates a new era for robot on the rail industry.

Making the interaction between the Arduino, RaspberryPI, DOBot, Handheld device and the electrical components was challenging and the incorporation of I2C communications as well as TCP/IP were incorporated. The coding in Python and Arduino IDLE was tested at the beginning of the project. Adding some development in Selenium interaction helped making the communication between so many different components and programming languages.

Having the physical demonstrator ready was key for the validation and verification of the concept. This is the second phase of the research where the physical demonstrator gave sufficient data to analyse and evaluate if the concept can be an accurate solution for the problematic that the rail industry is facing at the moment. Also, this stage meets the objective of verify and validate the concept in a small scale to increment its Technology Readiness Levels, contributing with important data that was incorporated on the main control system.

The tests performed on the physical demonstrator were performed based on the requirements of the project, having in mind that the most important system to test is the control framework. Been cable to regulate the movement of the train, identify a fault and start a repair operation was key for the project. The faults and the repair procedure were only demonstrative as this is a verification of the control system not the analysis of fault or the different repairing procedures that are on the industry. This verification and validation is for the control of the complete robot making it a plug and play system, meaning that any fault detection system and any repairing procedure is accepted by the controller, that the main reason of simulating the fault with brackets and the repairing with a 3D printing procedure. The capability of the control to decide that the fault was detected, and the repair was confirmed is what this research is about.

To achieve these objectives the robot should perform correctly and achieve all the requirements. The information collected from the verification and validation procedure shows that there is an insufficiency in the positioning of the robot and that is a critical requirement. Positioning the device properly has a high importance as even if the simulated fault is 3cm an error on the positioning will cause a failure of the repairing procedure, the concept of positioning the robot properly is a specific request for the control system.

Overall, the validation and verification of the system was achieved and raising the challenges that the RIRS will experience in a higher TRL, this will contribute to the second objective of the research,

The last phase of the research that is the scalability of the control system, for the RIRS into a higher TRL, was done by analysing the hardware and software components of the physical demonstrator. Also, the incorporation of new requirements that the new prototype must perform. The main integration on the necessities of the prototype is to be available to go on and off the rail tracks, for this a new vehicle was needed. The finding of an UGV robust enough to move over any surface was a considerable contribution, and the advantage that this UGV has ROS compatibility simplify the control system.

Scaling the concept into a higher TRL was taking in consideration the TRLs from Network Rail that can be seen in Appendix C the main focus was on the engineering side not the marketing and business tasks from the TRLs.

The control operational system for the RIRS is ROS. This was a requirement from Network Rail as the initiative Sift2Rail and In2Smart recommend the usage of new technologies available, in this case ROS is a complete operational system that allows the connection of several instruments and encourage the research on new technologies and industries.

The codification was made but unfortunately due to time constrains could not be tested fully. The control can be analysed by the following researcher and is available to revise and adapt for the next steps of this project.

7 Future work

This project is considered to be a long-term development as there are several details that can be incorporated to this concept.

In several conversations between Network Rail and Cranfield staff the implementation of the European Rail Traffic Management System (ERTMS) protocol was recommended as this system will give permission to the robot to start its procedure and realize the fault detection and repair actions to a certain location on the tracks. This will be analysed as the data obtained, at the time this research was made, was not sufficient to incorporate this robot to the ERTMS.

The physical demonstrator can be presented in different conferences showing that the concept turns to be a solution for autonomously repair and inspect the fault on rail tracks.

The test on the location of the robot is an urgent matter as this will dictate the future of the project. The localization of the UGV and the correct positioning of it, taking in consideration the length of the arm and the repair procedure has to be addressed and the incorporation of new elements like GPS and a clear way to decrease the error between the GPS and the real location should be considered for the future of the project.

The proper configuration to the Warthog is important as this UGV has the capability to perform on and off the tracks so it is important to consider that on the side of the tracks there are elements that have to be avoided, an obstacle detection system should be incorporated on the Warthog is recommended.

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APPENDICES

Appendix A Requirements

ID	PARENT	NAME	EXPLANATION
Prototype Simulation			
REQ 01	-	Design testing	The simulation shall test the system and concept design
REQ 01.1	REQ 01	5 inch gauge dimensions [1]	The virtual environment of the simulation shall respect the 5-inch gauge dimensions
REQ 01.1.1	REQ 01.1	5 inch tracks profile [1]	The track profile shall respect the 5-inch gauge
REQ 01.1.2	REQ 01.1	Scaled-down W6a gauge standard	The system shall be contained in the bounded area defined by the scaled-down W6a gauge standards
REQ 01.2	REQ 01	Prototype dimension	The simulation shall represent the real dimensions of the robotic system
REQ 01.2.1	REQ 01.2	Bogie dimensions	The simulation shall represent the real dimensions of the bogie
REQ 01.2.2	REQ 01.2	Robotic arm dimensions	The simulation shall represent the real dimensions of the robotic arm
REQ 01.2.3	REQ 01.2	3D printer head dimensions	The simulation shall represent the real dimensions of the 3D printer head

[1] It was decided to design the prototype by using the 5 inch railways model standard dimensions

REQ 01.2.4	REQ 01.2	Motors dimensions	The simulation shall represent the real dimensions of the motors
REQ 01.3	REQ 01	Prototype technologies	The simulation shall include the technologies used in the prototype
REQ 01.3.1	REQ 01.3	Inspection technologies	The simulation shall include the inspection technologies used in the prototype
REQ 01.3.2	REQ 01.3	Images streaming system	The simulation shall include the image streaming technologies used in the prototype
REQ 02		Demonstration process	The simulation shall represent the demonstration process
REQ 02.1	REQ 02	Demonstration process	The simulation shall represent the different phases of the demonstration process
REQ 02.1.1	REQ 02.1	Inspection stage	The simulation shall represent the different steps of the inspection stage
REQ 02.1.2	REQ 02.1	Repair stage	The simulation shall represent the different steps of the repair stage
REQ 02.1.3	REQ 02.1	Quality check stage	The simulation shall represent the different steps of the quality check stage
REQ 02.2	REQ 02.2	Interaction with the OI	The simulation shall display the interaction with the user through the OI

REQ 02.2.1	REQ 02.2	Inspection starting approval	The simulation shall display the interaction with the OI regarding the inspection starting the approval
REQ 02.2.2	REQ 02.2	Correct end-effector (x,y) position confirmation	The simulation shall display the interaction with the OI regarding the correct end-effector (x,y) position confirmation
REQ 02.2.3	REQ 02.2	Continue inspecting after not correct positioning	The simulation shall display the interaction with the OI regarding the decision about continue inspecting after not correct positioning
REQ 02.2.4	REQ 02.2	Correct repair confirmation	The simulation shall display the interaction with the OI regarding the correct repair confirmation
REQ 02.2.5	REQ 02.2	Continue inspection after correct repair	The simulation shall display the interaction with the OI regarding the decision to continue inspecting after correct repair
REQ 02.2.6	REQ 02.2	Stop and the following resume and reset options	The simulation shall display the stop option on the OI for freezing the system and the following reset and resume alternatives
REQ 02.3	REQ 02.3	Information flow to the RDMS	The simulation shall represent the information flow from the robotic system to the RDMS
REQ 02.3.1	REQ 02.3	Task N: started	The simulation shall represent the information flow to the RDMS when the inspection starts

REQ 02.3.2	REQ 02.3	Task N: defect position (x,y,z) – repair started	The simulation shall represent the information flow to the RDMS when the repair starts, with the communication of the defect's coordinates
REQ 02.3.3	REQ 02.3	Task N: correct repair – task closed	The simulation shall represent the information flow from the robotic system to the RDMS when the repair is correct and the task is closed
REQ 02.3.4	REQ 02.3	Task N: incorrect position – task closed	The simulation shall represent the information flow from the robotic system to the RDMS when the position is incorrect and the task is closed
REQ 02.3.5	REQ 02.3	Task N: incorrect repair – task closed	The simulation shall represent the information flow from the robotic system to the RDMS when the repair is incorrect and the task is closed
REQ 03	-	Controller logic basis	The simulation shall be developed so that it represents the controller logic basis
REQ 03.1	REQ 03	Components integration	The simulation shall be developed so that it represents the integration of the system different components
REQ 03.1.1	REQ 03.1	Components interaction	The simulation shall be developed so that it represents the communication and interaction

			among the system different components
REQ 03.1.2	REQ 03.1	Commented script	The simulation script shall be annotated to be easily understood and modified
REQ 03.2	REQ 03	Interactive windows	The interactive windows with the OI shall be connected to the simulation control
REQ 03.2.1	REQ 03.2	Lua - XML interaction	The Lua and XML languages shall be integrated into the script, to allow the interaction of the OI windows with the simulation control
REQ 03.2.2	REQ 03.2	Windows appearance	The windows appearance shall be organized so that the OI results user-friendly
ID	**PARENT**	**NAME**	**EXPLANATION**
REQ 01		**Reliable**	**The demonstrator must be able to work flawlessly every time**
REQ 01.1	REQ 01	Durable	The demonstrator needs to be able to withstand repetitive use
REQ 01.1.1	REQ 01.1	Suitable materials	The materials used must not fail and last for a long time without replacement
REQ 01.1.2	REQ 01.1	Withstand Transportation	The demonstrator must not be damaged when it is being transported
REQ 01.2	REQ 01	Easy to operate	The demonstrator must not be complex to set up
REQ 01.2.1	REQ 01.2	Intuitive	It must be obvious how to operate the demonstrator
REQ 01.2.2	REQ 01.2	Tuning Feature	Allows the demonstrator to be tweaked without having to change any code on a laptop

REQ 01.3	REQ 01	Simple design	The design should be as simple as possible to avoid integration issues
REQ 01.4.1	REQ 01.4	Modular	The design of the demonstrator should be made of interchangeable subsystems
REQ 01.4.2	REQ 01.4	Outsource components	Utilize outsourced components to save time and improve reliability
REQ 01.4	REQ 01	Low maintenance	The upkeep of the demonstrator should be kept to a minimum
REQ 01.4.1	REQ 01.4	Low wear components	Components will last a long time without replacement
REQ 01.4.2	REQ 01.4	No consumables	Consumables such as lubricant should not be necessary for the general use of the demonstrator to reduce maintenance
REQ 01.5	REQ 01	Low tolerances	Tolerances should below to allow for easy robot construction
REQ 02	**-**	**The representative of the TSC process**	**The demonstrator must relate to the TSC document**
REQ 02.1	REQ 02	Scalable	A scaled-down version of a full-sized system
REQ 02.1.1	REQ 02.1	Use 5-inch gauge track	5-inch was determined to be a suitable size to demonstrate the maintenance robot
REQ 02.1.2	REQ 02.1	Abide by relevant standards	Full-scale standards should be abided by to make it easy to scale up the demonstrator
REQ 02.2	REQ 02	Handheld tablet	The demonstrator should have a handheld to display process information and for the user to interact with the process
REQ 02.2.1	REQ 02.2	Stream images of robot location	To allow the operator to see what the robot sees
REQ 02.2.2	REQ 02.2	Emergency stop	Used to halt the demonstrator in an emergency
REQ 02.2.2	REQ 02.2	Initiate process	Button to initiate the demonstrator at the beginning of the process

REQ 02.2.3	REQ 02.2	Operator control	Allow the operator to control different variables during the demonstration
REQ 02.3	REQ 02	Visually similar	The demo must visually represent the full-size process
REQ 02.3.1	REQ 02.3	Abide by scaled-down W6a Gauge	This will ensure the demonstrator will have similar proportions to a full-scale version
REQ 02.3.2	REQ 02.3	Use the 3D printer to emulate defect fixing	This will imitate the welding process described in the TSC document
REQ 02.3.3	REQ 02.3	Mounted on 5-inch gauge train bogie	The bogie will emulate a full-scaled bogie
REQ 02.4	REQ 02	Autonomous control	The demonstrator must work autonomously
REQ 02.4.1	REQ 02.4	Use controller logic identified in TSC document	As the demonstration will need to be as close as possible to the process outlined in the TSC document
REQ 03	**-**	**Suitable for the exhibition environment**	**The demonstrator must be able to work within an exhibition environment**
REQ 03.1	REQ 03	Safe	The demonstrator must be safe within the exhibition environment
REQ 03.1.1	REQ 03.1	Assessment to evaluate risks	To identify any danger to the public during an exhibition
REQ 03.1.2	REQ 03.1	Risk mitigation procedure/ design	Risk mitigation should be designed into the demonstrator and the procedure
REQ 03.2	REQ 03	Easy to set up	The demonstrator must be quick and uncomplicated to set up
REQ 03.2.1	REQ 03.2	Use minimal tools	To reduce complexity and the skill needed to assemble the demonstration
REQ 03.2.2	REQ 03.2	Set up in minimal time	So that more time at the exhibition can be spent demonstrating rather than assembling
REQ 03.2.3	REQ 03.2	No heavy lifting	So that anyone can easily set up the demonstration

REQ 03.3	REQ 03	Aesthetically pleasing	The demonstrator must be visually appealing to draw attention from passers-by
REQ 03.3.1	REQ 03.3	Network Rail Livery	To allow the public to recognize the demonstration is associated with Network Rail
REQ 03.4	REQ 03	Fit into exhibition space	The demonstrator must be able to fit into the available exhibition space
ID	**Parent**	**Name**	**Notes**
REQ0001	REQ0001	REQ0001 Effectiveness, Performance & Suitability	The System shall meet the following requirements in terms of effectiveness, performance and suitability.
REQ0002	REQ0001	REQ0002 System Effectiveness	The System should meet the following effectiveness targets.
REQ0006	REQ0001	REQ0006 System Performance	The System should meet the following performance targets.
REQ0010	REQ0001	REQ0010 System Suitability	The System should meet the following suitability targets.
REQ0003	REQ0002	REQ0003 Geographical Coverage MoE	An MoE shall be defined of tasks executed successfully within a geographical area (TBD).
REQ0004	REQ0002	REQ0004 Network Disturbance MoE	MoE's shall be defined to quantify any disturbances to the railway network by use of the System.

REQ0005	REQ0002	REQ0005 Tunnel Inspection MoE	An MoE shall be defined to reflect tunnel inspection accuracy over time.
REQ0007	REQ0006	REQ0007 Communication Link MoPs	MoPs shall be defined to quantify communications links availability, quality, and reliability.
REQ0008	REQ0006	REQ0008 Navigation Accuracy MoPs	MoP's shall be defined to quantify the accuracy with which the navigation system shall be able to resolve positions.
REQ0009	REQ0006	REQ0009 Repair & Inspection MoPs	MoPs shall be established to define what constitutes a valid inspection or repair.
REQ0534	REQ0006	REQ0534 Inspection Performance	The Inspection Module shall detect defects with higher reliability than current operation in a shorter operating time.
REQ0011	REQ0010	REQ0011 Interventions MoS	The System shall define an MoS for the number of interventions needed to achieve task success.
REQ0012	REQ0010	REQ0012 Operational Life	The System shall be available for operations for 25years. The Life of the System or LoS shall be defined as 25 years.
REQ0013	REQ0010	REQ0013 Serviceability & Availability MoS	MoS for the System serviceability and availability shall be defined.

REQ0014	REQ0010	REQ0014 Task Failure Rate MoS	MoS shall be defined to quantify task failure rates when using the System.
REQ0015	REQ0015	REQ0015 Equipment Needs	The System shall meet the following equipment requirements:
REQ0017	REQ0015	REQ0017 Navigation	A robust navigation/localisation capability shall be required to give Navigation/geo-referencing to an appropriate level of accuracy (correct tracks) across the rail network (including tunnels)
REQ0018	REQ0015	REQ0018 Operational Data Logging	The System shall log and use the following operational data.
REQ0028	REQ0015	REQ0028 Operator Console Provision	The System shall provide dedicated operator consoles for control, monitoring and instrumentation and additional video monitors to display key parameters during operations.
REQ0037	REQ0015	REQ0037 Payload Needs	The Payload shall meet the following requirements.
REQ0040	REQ0015	REQ0040 System Linkages	The System shall have the following linkages to other Operating Environment systems.

REQ0054	REQ0015	REQ0054 Automotive Power	The VS shall not require external power.
REQ0055	REQ0015	REQ0055 Status Notification	The VS will display its status to the operator.
REQ0058	REQ0015	REQ0058 Visual Job Inspection	The operator shall be able to carry out a visual inspection to approve all repairs.
REQ0512	REQ0015	REQ0512 Static Operating Platform	The System shall provide a Static, Stable operating platform for payload operations
REQ0025	REQ0018	REQ0025 Task Historical Data	The System shall use historical data to improve task execution.
REQ0027	REQ0018	REQ0027 Unreported/ Misreported Data	The System shall log data to populate MoEs of unreported/misreported failures of repairs.
REQ0513	REQ0018	REQ0513 System Data logging	The system shall log data to populate MoEs, MoPs, MoSs
REQ0035	REQ0028	REQ0035 HCI and UI	The System shall incorporate suitable human computer interface (HCI) and user interfaces (UI) designed against recognised standards.

REQ0545	REQ0028	REQ0545 Operator Console Remote	
REQ0039	REQ0037	REQ0039 Tunnel Inspection Equipment	The ATIS shall incorporate the DIFCAM system as part of its suite of inspection equipment
REQ0560	REQ0037	REQ0560 Payload Philosophy	The Payload shall be a modular design allowing the fitting of a range of payload modules using standard interfaces between the VS and the payload (robotic arm).
REQ0043	REQ0040	REQ0043 Links to Operating Environment Condition Monitoring	The System shall have links to the wider Operating Environment condition monitoring system (Defect Management).
REQ0044	REQ0040	REQ0044 Links to Asset Condition Database	The system shall have linkages to the Asset Condition Database
REQ0053	REQ0040	REQ0053 Links to Signalling	The System shall have links to the extant Operating Environment signalling system.
REQ0552	REQ0040	REQ0552 Asset Data Management System	The System shall have links to the wider In2Smart specific Asset Data Management System

REQ0056	REQ0055	REQ0056 Consumables & Expendables Monitoring	The System shall provide to the Operator indications of consumables and expendables levels and state.
REQ0057	REQ0055	REQ0057 Safety Equipment Monitoring	The VS will provide indications to the Operator of safety equipment health.
REQ0059	REQ0059	REQ0059 Operating Environment Needs	The ATIS shall meet the following Operating Environment needs:
REQ0061	REQ0059	REQ0061 Natural Environment	The constraints on operation of the System as a function of limitations due to environmental effects such as weather.
REQ0064	REQ0059	REQ0064 Signalling	The VS shall respond to signals from the block based signalling system
REQ0066	REQ0059	REQ0066 VS Facilities	The RIRS shall be housed within an existing maintenance store when not in use.
REQ0563	REQ0059	REQ0563 Future Signalling	The VS design shall incorporate future compatibility with the European Train Control System (ETCS) on-board equipment
REQ0062	REQ0061	REQ0062 Natural	Any limiting ambient conditions affecting the operation of the

		Environment Driven Requirements	System, such as temperature or humidity limits, shall be defined and included in the System operating procedures.
REQ0063	REQ0061	REQ0063 Weather Constraints	Constraints on operation of the System due to ambient weather conditions shall be documented within the System operating procedures.
REQ0073	REQ0073	REQ0073 Operational, Support & Maintenance Needs	Proposed
REQ0074	REQ0073	REQ0074 Operational Needs	The System shall meet the following requirements:
REQ0075	REQ0074	REQ0075 System Operation Complexity	The system shall be simple to use and thus minimise the number of personnel needed for its operation.
REQ0076	REQ0074	REQ0076 Operation architecture	The VS shall be operated under the supervision of a correctly trained Operator
REQ0077	REQ0074	REQ0077 Operation interaction command levels	The operator will interact with the VS using high level commands

REQ0078	REQ0074	REQ0078 Concept of Operation	The System shall meet the following concept of operation requirements.
REQ0109	REQ0074	REQ0109 Levels of Automation	The System shall adopt appropriate levels of automation to meet efficiency targets.
REQ0079	REQ0078	REQ0079 Global Inspection	The System shall be capable of continuous inspection of rail infrastructure whilst roving.
REQ0080	REQ0078	REQ0080 Mission Operations Lifecycle	The System should follow the following mission phases.
REQ0097	REQ0078	REQ0097 Repair and Inspection Reporting	The System shall issue appropriate task status reports to the asset condition database.
REQ0098	REQ0078	REQ0098 System Operation Constraints	System operation shall be governed by the following constraints
REQ0102	REQ0078	REQ0102 System States	The System shall possess a number of configuration and operation states
REQ0103	REQ0078	REQ0103 System Job lists	The System shall be capable of receiving Job Lists that meet the following requirements.

REQ0107	REQ0078	REQ0107 Task Execution Goals	The System shall meet the following task execution goals
REQ0081	REQ0080	REQ0081 Mission Phase	The System shall have a mission phase consisting of the following operations.
REQ0087	REQ0080	REQ0087 Post-Mission Phase	The System shall have a post-mission phase consisting of the following operations.
REQ0092	REQ0080	REQ0092 Pre-Mission Phase	The System shall have a pre-mission phase consisting of the following operations.
REQ0082	REQ0081	REQ0082 Execute Task	The System shall have an execute task operation where the payload module executes the task.
REQ0083	REQ0081	REQ0083 Task Positioning	The System shall have a task positioning operation where elements of the payload module are positioned so as to be able to carry out the task.
REQ0084	REQ0081	REQ0084 Recovery to Facility	The System shall have a recovery to facility operation whereby the VS repositions at the hosting facility.
REQ0085	REQ0081	REQ0085 Select Job	The System shall have a Job select from the Job Schedule operation.

REQ0086	REQ0081	REQ0086 Transit to Job Operation	The System shall have a Transit to Job operation where the VS positions in the appropriate section.
REQ0088	REQ0087	REQ0088 Payload Post-Mission	The System shall have a payload post-mission operation where the need of each payload module is carried out following a mission.
REQ0089	REQ0087	REQ0089 Post-Mission Data	The System shall have a post-mission data process operation where data availability and security is ensured.
REQ0090	REQ0087	REQ0090 Storage Operations	The System shall have a storage operation where pre-storage tasks are carried out.
REQ0091	REQ0087	REQ0091 VS Checking	The System shall have a VS checking operation where post mission maintenance tasks are carried out.
REQ0094	REQ0092	REQ0094 Stores Replenishment	The System shall have a consumables and expendables replenishment operation.
REQ0095	REQ0092	REQ0095 Job Schedule Planning	The System shall have a Job schedule planning operation.
REQ0096	REQ0092	REQ0096 VS Readiness Checking	The System shall have a vehicle readiness checking operation.

REQ0561	REQ0092	REQ0561 Payload Module Preparation	The System shall have a payload module preparation operation as a manual task
REQ0099	REQ0098	REQ0099 Gauge Constraints	The System shall be designed to minimise gauge related constraints.
REQ0101	REQ0098	REQ0101 Signalling Constraints	System operation will observe restrictions dictated by the infrastructure signalling system.
REQ0104	REQ0103	REQ0104 Job List Composition	Job List shall comprise a prioritised schedule of individual 'jobs'.
REQ0551	REQ0103	REQ0551 Job Locations	The System shall receive job locations according to an In2Smart format specific location identifier (WP7)
REQ0553	REQ0103	REQ0553 Job Scheduling	The System shall order and schedule jobs based on urgency in accordance with WP9
REQ0114	REQ0114	REQ0114 System Safety & Security	The Systems shall meet the following requirements for safety & security.
REQ0115	REQ0114	REQ0115 Confidentiality & Security	System processes shall include those mandating the confidentiality and security of operations and any data produced by use of the System.

REQ0118	REQ0114	REQ0118 Operating Environment Safety	The System shall meet the following requirements for safety of the system infrastructure.
REQ0125	REQ0114	REQ0125 Safety Procedures	The System shall follow the following safety procedures.
REQ0128	REQ0114	REQ0128 Safety of Maintenance Regime	The System shall meet the following requirements for safety within the System maintenance regime.
REQ0134	REQ0114	REQ0134 Safety of Operational Regime	The System shall meet the following requirements for safety within the System Operational Regime.
REQ0116	REQ0115	REQ0116 Confidentiality Agreement	All classes of operator and members of the ROG shall be bound by a confidentiality agreement.
REQ0117	REQ0115	REQ0117 Document Markings	All supporting documentation materials will be marked according to the infrastructure managers procedures.
REQ0119	REQ0118	REQ0119 Cyber Security	The System shall be protected from the theft or damage to the hardware, software or the information within it, as well as from disruption or misdirection of the services it provides.

REQ0120	REQ0118	REQ0120 Gauge Compromising	The System shall detect and react appropriately to a compromised gauge constraint that prevents execution of the mission.
REQ0121	REQ0118	REQ0121 Line Blocking	The System shall detect and react appropriately to a blocked line that prevents execution of the mission.
REQ0122	REQ0118	REQ0122 Lineside Fires	The System shall not cause lineside fires.
REQ0123	REQ0118	REQ0123 Safety of Rail Electrification	The System shall operate safely without constraint in the presence of 3rd rail or overhead electrification systems.
REQ0124	REQ0118	REQ0124 Traffic Detection	The System shall incorporate a means of detecting other traffic using the railway network.
REQ0508	REQ0118	REQ0508 Collision Avoidance	The System shall avoid collisions with objects or humans.
REQ0517	REQ0118	REQ0517 Safe Operating Area	The system shall ensure compliance with a designated Safe Operating Area (SOA)
REQ0557	REQ0118	REQ0557 Payload Collision Avoidance	The System shall avoid payload collisions with infrastructure, objects or humans
REQ0127	REQ0125	REQ0127 Safety Case	A Safety case shall be defined in terms of the necessary evidence

			and procedures to meet the regulatory constraints.
REQ0131	REQ0128	REQ0131 Safe Recovery	The System shall be capable of safe recovery following failure and break down.
REQ0132	REQ0128	REQ0132 Safety Procedures	The Storage Facility shall be responsible for defining coherent operational procedures for incorporation safe System operations in the Storage Facility.
REQ0541	REQ0128	REQ0541 Maintenance Procedures	Maintenance procedures shall be defined
REQ0547	REQ0128	REQ0547 Transport & Handling Procedures	Transport and Handling procedures shall be defined
REQ0129	REQ0134	REQ0129 Coordination Between Teams	The System shall permit the safe working simultaneously with human maintenance teams within the same section of track.
REQ0130	REQ0134	REQ0130 Module Calibration For Safety	All payload modules shall be calibrated to preserve the System safety case.
REQ0133	REQ0134	REQ0133 Security of Mountings	All System components and moving parts shall be securely mounted.

REQ0135	REQ0134	REQ0135 Collision Risks to Third Party Personnel	The System shall provide proximity alerts to trespassers or maintenance staff when moving or preparing to move.
REQ0136	REQ0134	REQ0136 Crash & Fire Safety Procedures	The System shall develop safety procedures for actions in the event of a crash and/or fire.
REQ0137	REQ0134	REQ0137 Personnel On-board	The System shall incorporate procedures and components to support safe lone-working of personnel on-board the vehicle.
REQ0138	REQ0134	REQ0138 Reaction to Safety Signals	The System shall react appropriately in response to signals in abnormal/dynamic situations.
REQ0139	REQ0134	REQ0139 Redundancy in Navigation Systems	The System shall be designed to eliminate uncertainty in positioning.
REQ0140	REQ0134	REQ0140 Repair & Inspection Safety Regime	The System shall be designed to carry out safe repair and inspection tasks whilst in 'possession' but an aspiration to be able to operate in live traffic
REQ0141	REQ0134	REQ0141 Safety Interlocks	The System shall include safety interlocks such that all power or other associated hazards are

			removed from the System during defined emergency situations.
REQ0142	REQ0134	REQ0142 Speed & Braking Limitations	The System shall remain within safe speed limits and braking restrictions.
REQ0143	REQ0143	REQ0143 Users' Needs, Roles & Constraints	
REQ0174	REQ0143	REQ0174 Authority for Safe Operation	The operator shall be responsible for the execution of safety critical functions
REQ0175	REQ0143	REQ0175 Satisfactory Inspections	The operator shall be provided with the required information and be responsible for the acceptance of inspections
REQ0176	REQ0143	REQ0176 Safe operation	The operator shall be responsible for the safe operation of the VS
REQ0177	REQ0177	REQ0177 Business & Programme Needs	The following requirements shall meet the business goals and programme needs:
REQ0183	REQ0177	REQ0183 Intellectual Property	Consortium should decide a policy with respect to the intellectual property rights over property developed in the programme.

REQ0207	REQ0177	REQ0207 Engineering Lifecycle	The System shall be developed in a series of engineering phases:
REQ0221	REQ0177	REQ0221 Design Goals	The design of the System shall adhere to the following goals.
REQ0178	REQ0178	REQ0178 Business Goals	The System should achieve the following business goals:
REQ0179	REQ0178	REQ0179 System Aims	The System shall permit the inspection of tunnels and repair of rails with the objective requirement of incorporating additional roles.
REQ0181	REQ0178	REQ0181 System Performance	System success shall be demonstrated to meet the business case aims by the continual logging of performance indicators.
REQ0182	REQ0178	REQ0182 System Rationale	Through the application of technology, the System shall deliver efficiencies when compared to current work practices.
REQ0180	REQ0179	REQ0180 Tunnel Inspection Module (TIM) Objective	The Tunnel Inspection Module (TIM) shall provide maintenance teams with a valuable and detailed assessment of the tunnel condition and failure identification.

REQ0507	REQ0179	REQ0507 Rail Head Repair (RHR) Objective	The Rail Head Repair (RHR) module shall repair defects identified in the Defect Management database.
REQ0184	REQ0184	REQ0184 Operational Context	The System shall be operated according to the following requirements.
REQ0185	REQ0184	REQ0185 Change and configuration management, release control	Systems for change management, configuration management, release control shall be provided.
REQ0192	REQ0184	REQ0192 Country of Operation	The System shall be operated within the designated country only.
REQ0193	REQ0184	REQ0193 Design Authority	A Design Authority shall be appointed within the consortium.
REQ0194	REQ0184	REQ0194 Environmental Constraints	The System shall operate in accordance with the following environmental constraints:
REQ0195	REQ0184	REQ0195 Health and Safety	The System shall be capable of preparation and operation in conditions that comply with extant Health and Safety legislation operating within the designated country.

REQ0196	REQ0184	REQ0196 Hosting Facility Environment	The System shall operate with due regard to the environmental regulations extant within the hosting facility.
REQ0197	REQ0184	REQ0197 Insurance	System operational procedures shall make provision for adequate insurance cover.
REQ0201	REQ0184	REQ0201 Legal System Constraints	The System shall be operated within the constraints of the current legal and legislative system in the designated country.
REQ0202	REQ0184	REQ0202 Liaison with Trade Unions	Infrastructure Manager shall decide a policy to govern trade union liaison within the project.
REQ0205	REQ0184	REQ0205 System Operation Group (SOG)	An Infrastructure Manager group shall be established to oversee all operational matters regarding the system.
REQ0206	REQ0184	REQ0206 Regulatory Framework	The RIRS shall be compliant with the relevant high-level regulatory requirements.
REQ0222	REQ0184	REQ0222 Commissioning	The System shall be deemed to be commissioned when tested against a minimum of a Threshold set of requirements.
REQ0225	REQ0184	REQ0225 Design for Digital Railway	The System should be designed to be compatible with the Digital Railway.

REQ0533	REQ0184	REQ0533 Transport and Handling Procedure	The System shall have a defined transport and handling procedure.
REQ0186	REQ0185	REQ0186 Change and configuration management	The System shall be subject to a change and configuration control regime.
REQ0187	REQ0185	REQ0187 Modification Processes	The System shall comprise modification processes for design, test and operation following any changes to the baseline case for a period >= Life of System.
REQ0188	REQ0185	REQ0188 Modification Test Process	A process shall be defined that defines the exploration and enlargement of the System performance envelope including Concept and Production assemblies and applied from first commissioning for a period greater than, or equal to, the life of the system.
REQ0189	REQ0185	REQ0189 System maintenance and development	Processes and tools for systems development and maintenance shall be defined and applied throughout the LoS.
REQ0190	REQ0185	REQ0190 Systems for	Processes for change management, configuration

		Change Management	management and release control shall be defined and applied throughout the LoS.
REQ0198	REQ0197	REQ0198 Accidental Damage	The System shall be insured in respect of damage to the System in transit, during use and assembly and storage.
REQ0199	REQ0197	REQ0199 Storage Host Insurance	The Host site shall be insured in respect of damage to the System
REQ0200	REQ0197	REQ0200 Third-Party Liability	The System shall be insured in respect of liability to third-party personnel including the general public.
REQ0209	REQ0207	REQ0209 Technology Development (RIRS-CD) Phase Requirements	The RIRS-CD shall be designed to meet the following overarching capabilities:
REQ0210	REQ0209	REQ0210 Training Needs Analysis	A training needs analysis should be carried out during the concept phase of the programme.
REQ0211	REQ0209	REQ0211 RIRS-CD Functional Safety Requirements	Verifiable functional safety requirements shall be allocated to system modules where deemed necessary.

REQ0212	REQ0209	REQ0212 RIRS-CD Communications	The RIRS-CD phase shall assess potential datalink solutions
REQ0213	REQ0209	REQ0213 RIRS-CD Architecture	For the purposes of the RIRS-CD the Operator shall be co-located with the VS
REQ0214	REQ0209	REQ0214 RIRS-CD Development and Test	The RIRS-CD shall conduct a series of development and test activities in a representative environment
REQ0215	REQ0209	REQ0215 RIRS-CD Risks	The RIRS-CD phase shall address high risk areas to the programme and demonstrate performance in a representative environment.
REQ0226	REQ0221	REQ0226 Design for Safety	The System shall be designed to meet the following philosophy of safety.
REQ0232	REQ0221	REQ0232 Existing Interfaces	The System shall make best use of existing capabilities and equipment within all facilities in respect of operational, procedural, physical, hydraulic, cooling, electrical and signal interfaces and infrastructure.
REQ0233	REQ0221	REQ0233 GNSS Robustness	The System shall not rely on continuous access to a GNSS for navigation information.

REQ0235	REQ0221	REQ0235 Modularity in Design	The System shall be a modular system designed for re-use in future systems.
REQ0236	REQ0221	REQ0236 System Control Linkage Robustness	The System shall maintain safe functionality in the absence of continuous real-time linkage to the Operator
REQ0237	REQ0221	REQ0237 Technology Maturity	The initial concept phase shall use a higher degree of operator decision making to build confidence in the underlying technology and support any safety case.
REQ0223	REQ0222	REQ0223 Objective Requirements Definition	The System should meet as many of the objective requirements as is possible within the time and resource constraints of the development project.
REQ0224	REQ0222	REQ0224 Threshold Requirements Definition	The System shall meet all of the threshold requirements. All requirements shall be deemed Threshold requirements unless marked as Objective requirements.
REQ0227	REQ0226	REQ0227 Design for Crash & Fire Safety	The System shall be designed to minimise the risk to life and property in the event of crash or fire.
REQ0228	REQ0226	REQ0228 Hazard Analysis	The design shall include a complete hazard analysis and a

			definition of emergency states and recovery actions.
REQ0229	REQ0226	REQ0229 Mission Safety Regime Goal	The System shall initially be designed to carry out safe repair and inspection tasks whilst in 'possession' but ultimately be able to operate in live traffic.
REQ0230	REQ0226	REQ0230 Safe State	The System shall be capable of being manually placed into a safe state.
REQ0231	REQ0226	REQ0231 Unexpected Events	The System shall deal with unexpected events such that it always recovers to a safe condition.
REQ0511	REQ0510	REQ0511 Travelling Payload Collision Avoidance	The System shall avoid payload collisions with infrastructure or humans during travelling
REQ0558	REQ0557	REQ0558 Travelling Payload Collision Avoidance	The System shall avoid payload collisions with infrastructure, objects or humans during travelling

Appendix B TRL Tool Results

TRL Assment Report

START GAP ANALYSIS | RESET

PROJECT NAME	Physical Demonstrator	LATEST UPDATE	05/06/2019
TRL DESIRED	7		

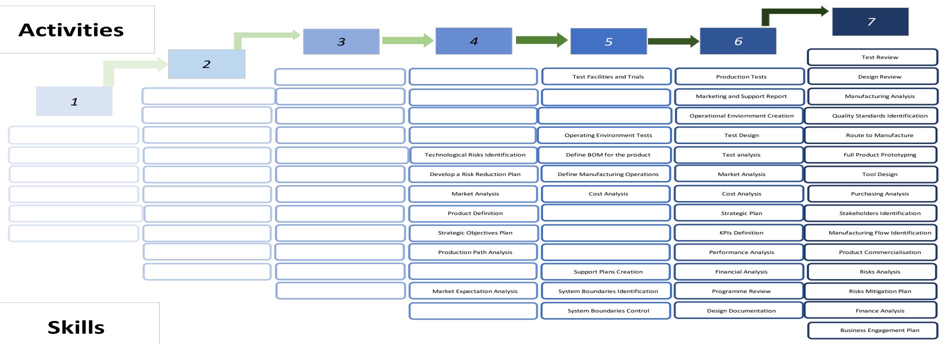
Version	Date	TRL Aimed
1.0	28/05/2019	7
2.0	31/05/2019	7
3.0	03/06/2019	7
4.0	04/06/2019	7
5.0	05/06/2019	7

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7
100%	100%	100%	50%	25%	0%	0%

TRL	REQUIREMENTS	Comments
1	Initial 'laboratory' research and opportunities to explore idea possible development routes	
1	Structured research into extant material and development of hypothesis	
1	Quick 'look-see' to ascertain the possibility / viability of the new / novel idea	
1	Articulate the opportunity, identify potential need and speculate exploitation	
2	Continued desktop research and analysis to consolidate and develop understanding of key principles and establish key variables	
2	Identification of key performance indicators	
2	Articulation of how to achieve proof of concept	
2	Documented desktop modelling to explore and establish expected technological parameters (including but not limited to factors / indicators / measures)	
2	Asset / Technology capability requirements defined along with key variables	
3	Development of technology to enable 'proof of concept' to be undertaken	
3	Range of recorded & qualitative experimental and modelling activities to validate main technology factors (including but not limited to indicators / measures)	
3	Produce functional description and commence identification of boundaries and interfaces with external systems / equipment	
3	Production of 'A models' to support / assist proof of concept	
3	Produce 'Space models' of equipment (may be 'virtual')	
3	Draft all technical requirements and specification	
3	Safety Analysis	
4	Production and bench qualification of 'B Models' utilising appropriately available technologies	
4	Development of asset / technology and refinement of function to demonstrate output performance and variability	
4	Identification and quantification of technology risks; Risk Reduction Plan	
4	Improved business plan, identification of route to market	
4	Improved project plan; better understanding of production path	
4	Interface testing and initial integration	
4	PESTLE implications and market expectations understood and planned / accounted for	
4	Human Factors	
5	Development / acquisition / access to trial and test facilities to validate technology (using B or C Models)	
5	Establish functional performance meets requirements and is repeatable	
5	Produce 'C Models' to be used in validation testing	
5	Produce production plans and establish cost of manufacture	
5	Commence environmental testing	
5	Asset / Technology Support Plans (RAMS, training, documentation, etc.)	
5	Performance boundaries understood and defined	
5	Asset / technology integrated with system; boundary conditions established, interfaces documented	
6	Production of small quantity of 'pre-production' assets /technology	
6	Asset / Technology demonstration events to support development and marketing	
6	Obtain access to / develop suitable operational (safe) test and demonstration environment(s)	
6	Verify cost of manufacture / selling price / market pricing regime	
6	Evidential confirmation of performance and function in an operational environment	
6	Complete design and development process to meet 'design freeze' status	
7	Formal qualification in an approved and representative operational environment	
7	Manufacture / build of production standard assets / technology	
7	Productionisation processes (build / test / certification, cost target, Quality Assurance, etc..)	
7	Supply chain development and stabilisation	
7	Risk mitigation and asset / technology maturation under formal change control	

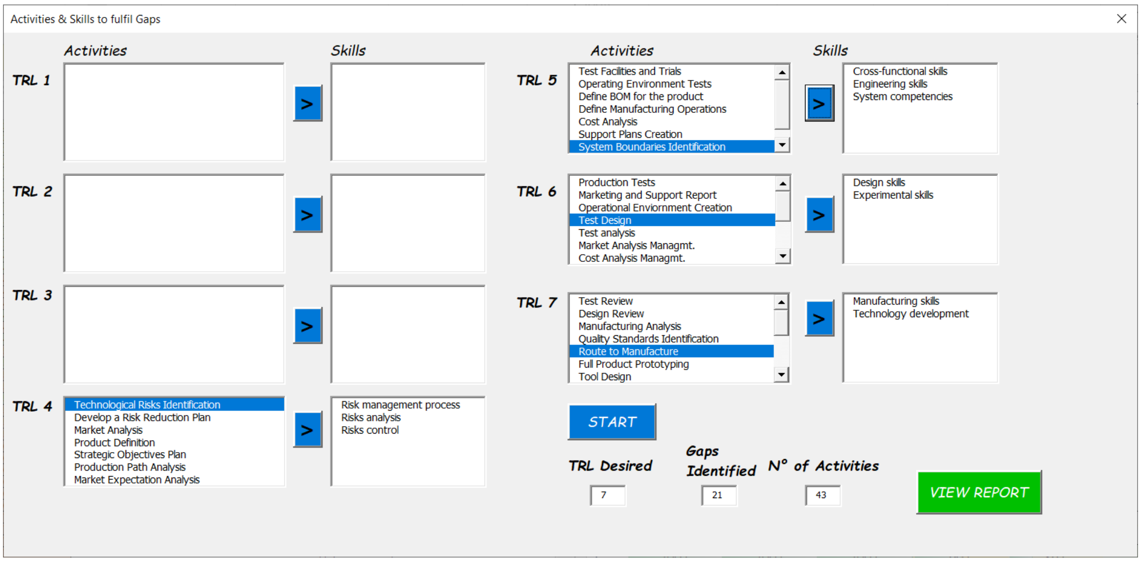
GAPS IDENTIFIED	21	NO ACTIVITIES	43

Activities



Skills

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7
Technology Development	Process Analysis	Reporting	Materials Design	Reporting	Change Management	Marketing
Product Development	Strategy Formulation	Statistics	Enterprise Resource Management	Risk Management	Quality Management	Business Competencies
R&D	Design	Mathematical	Supply Chain Management	Sustainability	Manufacturing	Quality Management
Engineering	Statistics	Test Knowledge	Safety Management	Societal Competencies	Finance	Purchasing Management
General Management	Technology Development	Product Acceptance	Management	Test Knowledge	Marketing	Manufacturing
Technical Competencies	Product Development	Sustainability	Risk Management	Statistics	Risk Management	General Management
	Strategy Competencies	Programming	Marketing	Manufacturing	Operations Analysis	Change Management
	Project Management	Safety Management	Statistics	Materials Knowledge	Tools Design	Finance


Activities & Skills to fulfil Gaps
Activities
Skills
TRL 1
TRL 2
TRL 3
TRL 4
Technological Risks Identification
Develop a Risk Reduction Plan
Market Analysis
Product Definition
Strategic Objectives Plan
Production Path Analysis
Market Expectation Analysis
Risk management process
Risks analysis
Risks control
Activities
Skills
TRL 5
Test Facilities and Trials
Operating Environment Tests
Define BOM for the product
Define Manufacturing Operations
Cost Analysis
Support Plans Creation
System Boundaries Identification
Cross-functional skills
Engineering skills
System competencies
TRL 6
Production Tests
Marketing and Support Report
Operational Enviornment Creation
Test Design
Test analysis
Market Analysis Managmt.
Cost Analysis Managmt.
Design skills
Experimental skills
TRL 7
Test Review
Design Review
Manufacturing Analysis
Quality Standards Identification
Route to Manufacture
Full Product Prototyping
Tool Design
Manufacturing skills
Technology development
START
TRL Desired
7
Gaps Identified
21
N° of Activities
43
VIEW REPORT

Appendix C Network Rail TRL classification

TRL	Requirements
1	Initial 'laboratory' research and opportunities to explore idea possible development routes
1	Structured research into extant material and development of hypothesis
1	Quick 'look-see' to ascertain the possibility / viability of the new / novel idea
1	Articulate the opportunity, identify potential need and speculate exploitation
2	Continued desktop research and analysis to consolidate and develop understanding of key principles and establish key variables
2	Identification of key performance indicators
2	Articulation of how to achieve proof of concept
2	Documented desktop modelling to explore and establish expected technological parameters (including but not limited to factors / indicators / measures)
2	Asset / Technology capability requirements defined along with key variables
3	Development of technology to enable 'proof of concept' to be undertaken
3	Range of recorded & qualitative experimental and modelling activities to validate main technology factors (including but not limited to factors / indicators / measures)
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3	Draft all technical requirements and specification
3	Safety Analysis
4	Production and bench qualification of 'B Models' utilising appropriately available technologies
4	Development of asset / technology and refinement of function to demonstrate output performance and variability
4	Identification and quantification of technology risks; Risk Reduction Plan
4	Improved business plan, identification of route to market
4	Improved project plan; better understanding of production path
4	Interface testing and initial integration
4	PESTLE implications and market expectations understood and planned / accounted for
4	Human Factors
5	Development / acquisition / access to trial and test facilities to validate technology (using B or C Models)
5	Establish functional performance meets requirements and is repeatable
5	Produce 'C Models' to be used in validation testing
5	Produce production plans and establish cost of manufacture
5	Commence environmental testing
5	Asset / Technology Support Plans (RAMS, training, documentation, etc.)
5	Performance boundaries understood and defined
5	Asset / technology integrated with system; boundary conditions established, interfaces documented
6	Production of small quantity of 'pre-production' assets /technology

6	Asset / Technology demonstration events to support development and marketing
6	Obtain access to / develop suitable operational (safe) test and demonstration environment(s)
6	Verify cost of manufacture / selling price / market pricing regime
6	Evidential confirmation of performance and function in an operational environment
6	Complete design and development process to meet 'design freeze' status
7	Formal qualification in an approved and representative operational environment
7	Manufacture / build of production standard assets / technology
7	Productionisation processes (build / test / certification, cost target, Quality Assurance, etc..)
7	Supply chain development and stabilisation
7	Risk mitigation and asset / technology maturation under formal change control

TRL	**Activity**
1	Horizon Scanning
1	Route to development
1	Materials Review
1	Hypothesis Development
1	Viability Study
1	Opportunities Analysis
2	Research Analysis
2	Key Principles Analysis
2	Key Variables Identification
2	KPIs Identification
2	Proof of Concept Analysis
2	Strategy to Proof of Concept
2	Technical Parameters Analysis
2	Technology Modelling
2	Technology Capability Definition
2	Comparison with Key Variables
3	Development in a lab environment
3	Proof of Concept Understood
3	Experiments in a lab environment
3	Technology Factors Demonstration
3	Commence Boundaries Identification
3	Modelling technology to Support Concept
3	Virtual Experiments in Laboratory
3	Software Experiments
3	Technical Requirements Identification
3	Specification Analysis
3	Safety Analysis
3	Impact Analysis
4	Production Requirements Identification
4	Technological Functions Development Operating Environment

4	Output Performance Analysis
4	Variability Analysis
4	Technological Risks Identification
4	Develop a Risk Reduction Plan
4	Market Analysis
4	Product Definition
4	Strategic Objectives Plan
4	Production Path Analysis
4	Tests Integration
4	Market Expectation Analysis
4	Human Factors Impact
5	Test Facilities and Trials
5	Functional Performance Tests
5	Requirements Fulfilment
5	Operating Environment Tests
5	Define BOM for the product
5	Define Manufacturing Operations
5	Cost Analysis
5	LCA
5	Innovation Roadmap
5	Continuous Reporting
5	Support Plans Creation
5	System Boundaries Identification
5	System Boundaries Control
6	Production Tests
6	Marketing and Support Report
6	Operational Enviornment Creation
6	Test Design
6	Test analysis
6	Market Analysis Managmt.
6	Cost Analysis Managmt.
6	Strategic Plan
6	KPIs Definition
6	Performance Analysis
6	Financial Analysis
6	Programme Review
6	Design Documentation
6	Test Review
6	Design Review
7	Manufacturing Analysis
7	Quality Standards Identification
7	Route to Manufacture
7	Full Product Prototyping
7	Tool Design
7	Purchasing Analysis

7	Stakeholders Identification
7	Manufacturing Flow Identification
7	Product Commercialisation
7	Risks Analysis
7	Risks Mitigation Plan
7	Finance Analysis
7	Business Engagement Plan

ID Activity	Skills
1	Engineering skills
1	R&D skills
1	Technological competencies
2	Engineering skills
2	R&D skills
2	Technological competencies
3	Product competencies
3	Technical skills
3	Mechanical Engineering
4	Engineering skills
4	R&D skills
4	Technological competencies
5	Engineering skills
5	R&D skills
5	Technological competencies
6	Engineering skills
6	R&D skills
6	Technological competencies
7	Research methodologies
7	Technology competencies
8	Engineering skills
8	R&D skills
8	Process analysis
9	Process analysis
9	Statistical skills
9	Mathematical skills
10	Statistical skills
10	Mathematical skills
10	Process skills
11	Engineering skills

11	Technology competencies
11	Product competencies
12	Strategic skills
12	Project skills
12	Risk mitigation
13	Statistical skills
13	Product acceptance
13	Product development
14	Design skills
14	Technical skills
14	Technology competencies
15	Technology competencies
15	Technical skills
16	Risk mitigation
16	Statistical skills
17	Engineering skills
17	Reporting skills
17	Statistical skills
18	Technology development
18	Product skills
19	Statistical skills
19	Reporting skills
20	Technology Development
20	Trasversal competencies
21	Sustainability competencies
21	Environmental skills
21	Product lifecycle
22	Technology Design
22	Product competencies
22	Engineering skills
22	System competencies
23	Programming skills
23	Computational skills
23	Statistical skills
24	Programming skills
24	Computational skills
25	Product lifecycle
25	Technology skills
25	Supply chain competencies
26	Product acceptance
26	Product specifications
27	Safety procedures
27	Quality management

27	Product management
28	Risk skills
28	Risk management
28	Product lifecycle
29	Manufacturing skills
29	Tools competencies
29	Management skills
30	Technology development
30	Technological skills
31	Statistical skills
31	Management skills
31	Operations analysis
32	Statistical skills
32	Mathematical skills
33	Risk management process
33	Risks analysis
33	Risks control
34	Risks financing
34	Enterprise risks
34	Insurance knowledge
34	Project management
35	Marketing competencies
35	Product development
36	Product development
36	Technical competencies
37	Strategic competencies
37	Cross-functional skills
37	Management skills
38	Product lifecycle
38	Technology roadmap
38	Project management
39	Statistical skills
39	Mechanical competencies
40	Marketing competencies
40	Product competencies
40	Supply chain competencies
41	Societal competencies
41	Management skills
42	Experimental skills
42	Statistical skills
43	Mechanical engineering
43	Tests competencies
44	Cross-functional skills

44	Technological development
45	Tests competencies
45	Mathematical skills
46	Manufacturing skills
46	Materials competencies
47	Manufacturing skills
47	Supply chain competencies
47	Materials competencies
48	Finance management
48	Risk management
49	Sustainability competencies
50	Technology development
50	Product development
51	Reporting skills
52	Cross-functional skills
52	Reporting skills
53	Cross-functional skills
53	Engineering skills
53	System competencies
54	System competencies
54	Product boundaries
55	Manufacturing skills
55	Tests competencies
56	Marketing competencies
56	Change management
57	Design skills
57	Simulation skills
58	Design skills
58	Experimental skills
59	Operations analysis
59	Statistical skills
60	Marketing competencies
60	Supply chain competencies
61	Finance management
61	Risk management
62	Corporate strategy
62	Risk management
63	Operations analysis
63	Operations management
64	Statistical skills
64	Engineering skills

64	Operations management
65	Finance management
65	Business knowledge
66	Reporting skills
67	Design skills
67	Reporting skills
68	Reporting skills
68	Tests competencies
69	Reporting skills
69	Business knowledge
70	Manufacturing skills
70	Engineering skills
70	Technical competencies
71	Quality management
71	Quality assurance
71	Finance management
72	Manufacturing skills
72	Technology development
73	Design skills
73	CAD knowledge
73	Technology development
74	Mechanical skills
74	Manufacturing skills
75	Purchasing competencies
75	Marketing competencies
76	Business knowledge
76	Market knowledge
77	Manufacturing skills
77	Management skills
77	Change management
78	Product acceptance
78	Product requirements
79	Risk management
79	Risk analysis
80	Reporting skills
80	PFMEA
81	Finance management
81	Change management
82	Leadership skills
82	Business knowledge