

CRANFIELD UNIVERSITY

GERARD TAYKALDIRANIAN

MULTIDISCIPLINARY DESIGN PROCESS OBSERVATIONS OF A
“TRAIN FRONT CAB CLEANING ROBOT” PROJECT

SCHOOL OF AEROSPACE TRANSPORT AND MANUFACTURING
Research in Manufacturing

MSc by Research
Academic Year: 2016 - 2017

Supervisor: Professor Tetsuo Tomiyama
August 2017

CRANFIELD UNIVERSITY

SCHOOL OF AEROSPACE TRANSPORT AND MANUFACTURING
Research in Manufacturing

MSc by Research

Academic Year 2016 - 2017

GERARD TAYKALDIRANIAN

MULTIDISCIPLINARY DESIGN PROCESS OBSERVATIONS OF A
“TRAIN FRONT CAB CLEANING ROBOT” PROJECT

Supervisor: Professor Tetsuo Tomiyama
August 2017

© Cranfield University 2017. All rights reserved. No part of this
publication may be reproduced without the written permission of the
copyright owner.

ABSTRACT

This thesis presents an observation of the designed development process of a train cab front cleaning robot that was demonstrated by building a scaled prototype which was presented during the robotics and autonomous systems dissemination event held by RRUKA.

The design process consisted of the systems, mechanical, and software designs which were completed in a multidisciplinary engineering project. Self-reflective observation was conducted to identify problems in decision making, lack of expertise which led to delays, cost increase of the project. The challenges of a multidisciplinary academic design project were addressed during the integration phase when all the system came together in order to build the robot. The problems faced during the project were categorized into external, managerial, logistical, and design issues, which were in turn analysed through

Keywords:

Robot design, Self-reflection observation, Systems integration, Academic design challenges, Design process, Multidisciplinary.

ACKNOWLEDGEMENTS

I would like to express my appreciation and gratitude to Professor Tetsuo Tomiyama and RSSB for providing me the funding opportunity to work on this project.

I would like to thank all those involved in the project for all the support and help provided throughout the project period which reflected at the end by the successful demonstration of the prototype in front of the industrial partners.

Finally I would like to thank Cranfield University for providing the perfect environment for completing my research.

TABLE OF CONTENTS

ABSTRACT	1
ACKNOWLEDGEMENTS.....	2
LIST OF FIGURES.....	5
LIST OF TABLES	7
LIST OF ABBREVIATIONS.....	8
1 INTRODUCTION.....	9
1.1.1 Background	9
1.2 Aim and Objectives	10
1.3 Thesis outline.....	11
2 LITERATURE REVIEW	12
2.1 Mechanical Cleaning History	13
2.2 Train Cleaning Automated Systems.....	15
2.3 Design Process.....	17
2.3.1 Robotic Design Process	20
2.3.2 Systems Engineering	21
3 METHODOLOGY	22
3.1 Define	22
3.1.1 Project Setting.....	23
3.1.2 Participation and Work Sequence	23
3.2 Measure.....	25
3.3 Analyse	25
4 DESIGN PROJECT	27
4.1 Introduction	27
4.2 Product Concept Proposal	4
4.3 Requirement Gathering.....	5
4.4 System Architecture.....	5
4.5 Conceptual Design.....	6
4.6 Control Software	8
4.7 Mechanical Design.....	10
4.8 Prototype mechanical design.....	10
4.8.1 Prototype.....	11
4.9 Initial Finite element Analysis for full scale rail beams	16
4.9.1 Finite element analysis results	17
4.10 Integration.....	20
4.11 Testing.....	21
4.11.1 Force Analysis.....	21
4.11.2 Test Results	23
4.11.3 Constant Force Control	23
4.11.4 End-effector Orientation with Respect to the Surface	24
4.11.5 Path Planning Trajectory	25

5 RESULTS.....	27
5.1 Project Observations.....	27
6 DISCUSSION	30
6.1.1 Integration Issues	31
6.1.2 Multidisciplinary Project.....	31
6.1.3 Process Control.....	32
7 CONCLUSION	34
REFERENCES.....	35
APPENDICES	38
Appendix A Depot Visits	38
Appendix B Weight Estimation.....	41
Appendix C Prototype assembly.....	42
Appendix D Finite Element Bending Moment Results	44
Appendix E Monthly Progress Report to RSSB Template	47
Appendix F Baxter robot	51
Appendix H Publications	52

LIST OF FIGURES

Figure 1 Future prediction of jobs taken over by machines [5].	13
Figure 2 Clapham carriage washer plant [6].	14
Figure 3 One of the early fully automatic car washers [8].	14
Figure 4 ISTOBAL train washing installation [9].	15
Figure 5 Christ Wash Systems train wash C7000 [10].	16
Figure 6 Left: Hoover robot vacuum cleaner. Right: Serbot GEKKO robot for large area glass façades	17
Figure 7 Pahl & Breitz product development process [15].	18
Figure 8 Flowchart for the development of a gripper robot [17]	20
Figure 9 Systems engineering process development V-model.	21
Figure 10 Five steps of DMAIC [20]	22
Figure 11 Individual participation during design project.	24
Figure 12 Sequence of the design tasks blue in CU, Orange HWU	24
Figure 13 Number of passenger journeys with respect to years from 1950 to 2016 [27].	27
Figure 14 Left: Electric train side wash Willesden depot, London. Right: Diesel train side wash Wembley depot, London.	28
Figure 15 Left: Manual cleaning of diesel train Wembley depot, London. Right: Manual cleaning of electric train Willesden depot, London.	28
Figure 16 High speed trains front cab shapes [28].	3
Figure 17 Product development cycle for the front cab cleaning robot.	4
Figure 18 Proposed conceptual designs during the workshop held in Heriot-Watt University[23].	7
Figure 19 (a) surface scan path planned on a flat surface. (b) The surface scan path projected onto a non-flat surface.	9
Figure 20 Conceptual design by Garcia [23]	11
Figure 21 Industrial XYZ gantry system from HepcoMotion [32]	12
Figure 22 Belt driven carriage gantry unit [33].	12
Figure 23 Detailed CAD model of the scaled Robot.	15
Figure 24 1/8th scaled model of train front cleaning robot during RRUKA event at the Science Museum in May 2017	15

Figure 25 Rail Cross section for finite element analysis.	16
Figure 26 End-effector gantry rail displacement.....	18
Figure 27 Horizontal gantry rail displacement.	19
Figure 28 Vertical gantry rail displacement.....	20
Figure 29 Hired Van to simulate the front cab of the train.	22
Figure 30 (A) Brush connected to a force sensor. (B) Brush that is used for manual front cab cleaning.....	22
Figure 31 Force/Torque sensor from ATI Industrial Automation.....	22
Figure 32 Normal force generated in the direction perpendicular to the 3D surface with respect to time.....	24
Figure 33 Torques tangent to sweeping surface.	24
Figure 34 Initial path plan trajectory error in two dimensional graph showing x- axis and y-axis.....	25
Figure 35 Path plan trajectory in two dimensional graph x-axis and y-axis after debugging the code	26
Figure 37 Gantt chart comparing planned and actual duration of each design phase.....	30
Figure 37 Krslin KVA and SVA table [22].	40
Figure 38 Front CAB model.....	42
Figure 39 3D printed components	42
Figure 40 Horizontal Gantry motor attachment.....	43
Figure 41 Gantry assembly at Heriot-Watt University.....	43
Figure 42 Bending moments acting on end-effector gantry.....	44
Figure 43 bending moment acting on horizontal gantry.....	45
Figure 44 Bending moment acting on vertical gantry.	46
Figure 45 Baxter robot used to test force sensor control [26]	51

LIST OF TABLES

Table 1 System design variables and operations summary [22].	6
Table 2 gantry properties and initial deflection calculations.	13
Table 3 1/8 scale prototype information.	14
Table 4 weight and length of each gantry unit.	16
Table 5 Initial forces, moments, and constraints of nodes.....	17
Table 6 Applied brush force results	23
Table 7 Time taken in each design phase	27
Table 8 Categorized Issues faced during the design process	28
Table 9 Result analysis summary for issues encountered	29
Table 10 Robot weight estimation	41

LIST OF ABBREVIATIONS

3D	3 Dimensional
CAD	Computer Aided Design
CU	Cranfield University
DOF	Degrees Of Freedom
DTM	Design Theory and Methodology
FEA	Finite Element Analysis
FBS	Function-Behaviour-Structure
HWU	Heriot-Watt University
IT	Information Technology
KVA	Key Value Attributes
RAS	Robotic Autonomous Systems
ROS	Robotic Operating System
RRUKA	Rail Research UK Association
RSSB	Rail Safety and Standards Board
SE	Systems Engineering
SBCE	Set Based Concurrent Engineering
SVA	Secondary Value Attributes

1 INTRODUCTION

An effective design process relies heavily upon effective decision making [1], but as the complexity of the process increases it is inevitable that problems from design mistakes will occur during the project, and design changes have to be made in order to minimize project delays and unforeseen costs. Therefore, it is necessary to analyse and sort the problems occurring in the design process. The design project described in section 4 “Feasibility study of a train cab front cleaning robot” was aimed to improve the design development process through analysing project setbacks. Of particular interest was the communication, knowledge transfer, and environment settings in the multidisciplinary project during the design development process.

1.1.1 Background

Engineering design process is a formulation of a plan or scheme to assist an engineer in creating a product [2]. According to Tayal, the process is a multi-step process which includes research, conceptualization, feasibility, assessment, establishing design requirements, preliminary design, detailed design, production planning and tooling design, and finally production. All the steps are interrelated and it is very common to find design issues which will take the project back to earlier design stages leading to delays, and exceeding assigned budget for the project. This section, will first provide a brief description on the topic. Then a discussion of the problems arising from multidisciplinary projects will be followed including the experimental settings of observing the “Train cab front cleaning robot” project. Finally, an explanation of why this research was done.

There has been growing recognition of importance in university and academic research to industrial innovation and performance, many universities have become more directly involved in the commercialization of their research [3]. For this reason projects in partnership with industry professionals have been an active area of research involving university-industry interactions. The project observed was part of a multidisciplinary design project which involved engineers from academia and related rail industry professionals which occurred over a

timescale of one year resulting in the development of a functional scaled prototype concluding the feasibility study. Over the course of the design process problems were noted specially during the integration phase of all the systems designed.

Problems during the design phase are inevitable to happen, design processes and standards are used to minimize the effect of problems on the overall design process. As a university project, engineering students lack design experience in an industrial environment, this inexperience increases the complexity of projects such as the “Train cab front cleaning robot”. By analysing steps and decisions made leading to design issues and delays, a more structured approach can be suggested for such multidisciplinary design project. This new approach may be used to raise early flags highlighting mistakes and preventing the accumulation of bad decisions. Self-reflection observation was used to describe various setbacks during the development process of the project.

What decisions created design problems? How can issues be identified in a multidisciplinary design project

1.2 Aim and Objectives

This project was part of a feasibility study funded by RSSB to introduce several automated systems in rolling stock maintenance facilities. The train cab front cleaning robot will provide an efficient way of cleaning as well as lowering the risks of exposing maintenance personal to health and safety hazards by replacing manual labour with the automated system.

The work in this thesis aims to identify the issues encountered during the design phase of the train front cab cleaning robot scaled prototype. This was achieved by observing the development process of this project which was done by Cranfield University and Heriot-Watt University.

The above aims raise the following objectives:

- Build and demonstrate a 1/8 scale model of the robot to prove the functionality and concept behind the design.

- Test the integrated systems
- Identify and categorize Issues
- Determine the effect of the issues on the project progress.

1.3 Thesis outline

A brief summary on each chapter is listed in this section.

- 1- Introduction: This part provides general information about the thesis topic, research background, aim and objectives, and the summary of chapters.
- 2- Literature Review: This part summarises the knowledge and work done in related fields.
- 3- Design Project: This section was written to help the reader understand how the project was structured and what was done by each member involved. It explains each part of the design with the major decisions made on individual basis and team basis.
- 4- Methodology: This part presents the approach used by the author to analyse design process mistakes that occurred in the Cab front cleaning robot feasibility study.
- 5- Results: This part provides the observation summary with major problems categorized and discussed in detail.
- 6- Discussion: This chapter summarizes talks about the issues major issues faced, and what could have been done to prevent.
- 7- Conclusion: This section concludes the research with summary of the outcomes and lessons learned from the robot design project

2 LITERATURE REVIEW

The idea of having robotic automated systems is not as new as you might think. According to history, early Greek myths include concepts of animated statues or sculptures [4]. RAS developed from simple to complex systems throughout history using the technology of that time. Today RAS can be found in every human application whether it's on land, maritime, air, or space.

As technology advanced more RAS were developed in various areas, and machines are forecasted to take over more jobs that are currently done by humans [5]. The RAS will not be limited to a specific job varying from critical thinking to manual tasks as shown in Figure 1, where it is predicted that in less than 50 years machines will be capable of undertaking all human tasks. This subject is currently under debate whether mankind will benefit from having machines doing all the work. On the other hand, one can't deny the fact of having machines taking over or participating in certain jobs that have high safety risks for humans or in areas where human error can cause loss of lives.

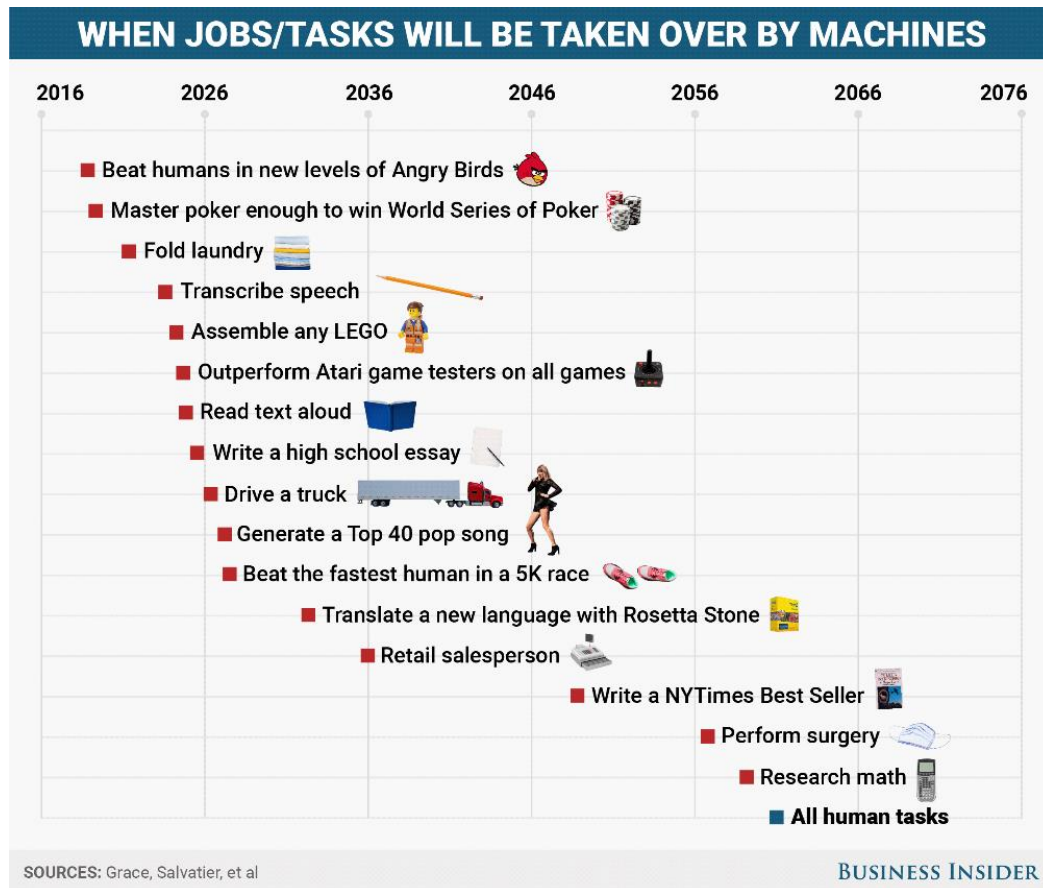


Figure 1 Future prediction of jobs taken over by machines [5].

2.1 Mechanical Cleaning History

Simple Mechanical train washers were introduced to Clapham carriage washer plant in 1944. The plant used to clean the sides of carriages using high-powered jets of water and dozens of static revolving abrasive cloths [6] as shown in Figure 2.



Figure 2 Clapham carriage washer plant [6].

The first automated cleaning system adjusted its brushes to the geometry of cleaning surfaces were for transport vehicles built in 1950s in Seattle. As the demand on vehicles increased during that period fully mechanized car washing systems were being installed across America [7]. Figure 3 below shows one of the first automatic washers which was developed by the German company WESUMAT [8]. The car used to enter the washing area where it stops in a specified spot and the washer then circles around the car with a revolving brush that cleans all the surfaces.



Figure 3 One of the early fully automatic car washers [8].

2.2 Train Cleaning Automated Systems

If we look at what the market is offering today, it can be easily noticed that there are many companies that offer automated system solutions for front cab train cleaning. Most of the companies offer full services from installing to maintaining the system. ISTOBAL [9] a Spanish company has been designing and manufacturing car care solutions since 1950's. Together with their French subsidiary FDI+, they are supplying automated washing systems shown in Figure 4 that clean the sides as well as the fronts of tram cabs. The problem with their system is the custom-made installation for each type of tram.

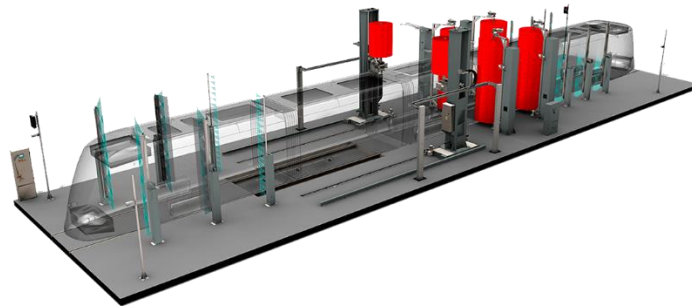


Figure 4 ISTOBAL train washing installation [9].

One of the leading companies in train washing is Christ Wash Systems, They develop train washer units that can be stationary, semi-stationary or mobile for trains and trams [10]. Figure 5 shows the C7000 washer with long cylindrical brushes which is used for both side and front cab surface cleaning. The use of cylindrical brushes will cover more area in less time, but this method does not clean efficiently according to some of the managers of depots that were visited for data and requirement gathering. Hence such cleaning systems are not used in the visited depots where train front cabs are cleaned manually. When looking at the cylindrical brush shape it consists of many long filaments that hit the surface randomly with a low force while the brush rotates. This is more effective in side cleaning since less dirt accumulates on the sides of train carriages than the end nose of the front cab.



Figure 5 Christ Wash Systems train wash C7000 [10].

Other companies such as Interclean, Raimondi, and Westmatic-technology provide solutions similar to Christ Wash systems. One particular observation from the type of train and tram picture gallery of those companies only show simple flat cab ends with slight curvature in some designs.

These mechanisms don't have specific feedback of applied force since the systems recognize the front cab surface as one entity and the cleaning procedure is not targeted differently depending on the surface shape. This meaning that some areas along the rotating cylindrical brush are cleaned better than other areas. These types of washing mechanisms do not suit rail companies with different types of trains or trains with complicated front cab surface curves.

Cleaning robots that can trace complicated surfaces in 3 Dimensions were found. This finding cannot be 100% confirmed but what can be said is that cleaning complicated surfaces using robotic arms that can generate a 3D path plans for cleaning such surface is relatively a new area. Cleaning robots are becoming affordable for household and industry use, ranging from house cleaning to more complex mall and skyscraper windows cleaning. Such type of domestic robots listed in [11] operate on a 2D planar environments. Companies such as Dyson, Hoover, Samsung, among others are competing to produce robot vacuum cleaners such as the ones found in Figure 6 (Left). Other robotic companies such as Serbot are targeting solar panel and glass facades on buildings

Figure 6 (Right). These types of cleaning robots are cleaning flat surfaces, which makes path planning simpler. For a train things are more complicated, since the surface is not flat and some trains have more complicated 3D shapes making the robotic mechanism design more complex.



Figure 6 Left: Hoover robot vacuum cleaner. Right: Serbot GEKKO robot for large area glass façades

There is little literature concerning such types of manipulator robots that can deal with 3D surfaces [12]. One paper considered the problem of null space minimization in path planning of 3D surfaces for redundant manipulators. This paper also states the importance of 3D surface coverage due to the many interesting potential applications.

2.3 Design Process

The design and building process requires a wide-range of engineering expertise to successfully have an end product that meets the design requirements. Different experts and design companies suggest various processes of design and integration methods to build their specified product. Although the start and end procedures are the same for any product development the steps in between differ depending on the complexity, size, and application of the product. Substantial academic research can be found on product development and design processes, but there are limited documented comprehensive research on the practical and wide application of optimizing the product design process [13]. Design engineers describe Pahl & Beitz “Systemic Approach” for a design process as the Bible of design methods [14]. Pahl & Beitz [15] wanted to create a general design approach applicable to broad areas of

engineering instead of having specific processes for specialist fields. Figure 7 below shows the product development systematic process suggested by Pahl & Beitz, the process is categorized into four phases which are all linked and cycled until the required product is developed by finding the best design solution.

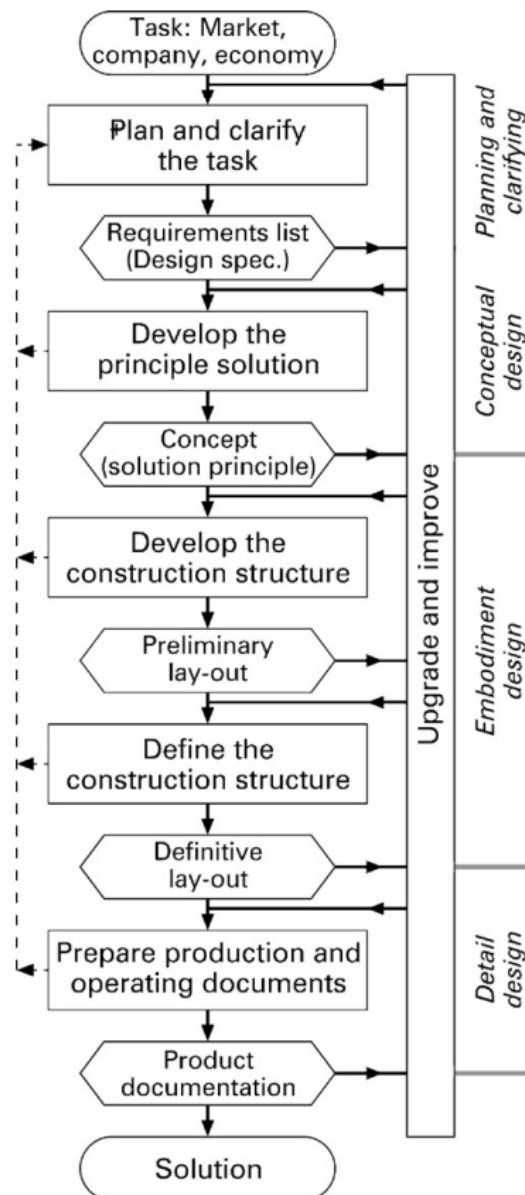


Figure 7 Pahl & Beitz product development process [15].

According to them this systematic approach will reduce workload, design errors, and cost. However, Jensen and his team [14] argue that the systematic approach will constrain the users to a degree that adds difficulty to the design process due to the set of particular instructions that has to be followed eliminating the methods

that rely on chance and out of the box thinking. Pahl & Beitz consider these non-systematic processes as 'seldom' and they do not necessarily produce logical steps that raise the chance to find the best solution [14]. Jenson's team tried to argue the design process from another point of view when they introduced the study of Ethnomethodology, which is the study to "understand the methods that people deploy (ethno-methods) as they go about their daily business"[14]. The case studies were conducted by students as part of a 'Design Methods' course at the Technical University of Denmark. The study targets engineering companies that follow a process which the students have to make observations on how the process is applied, what is the intended outcome along with other series of questions that built up the case study. One of the most important outcomes of this study was the indication that the methods applied are sometimes routinely changed, skipped, and squeezed as a result of pressures from the management due to lack of budget and a limited project timescale. The paper finally concludes that design methods should be studied in a way that takes into account the work practice of effective engineers leading to findings of different methods that can improve the design process.

Tomiyama [16], takes a step towards categorizing design methodologies applied in industrial and educational projects. The theories and methodologies that were found most practically useful are "math-based methods", "methodologies to achieve concrete design goals", and "process methodologies", while in educational projects in addition traditional theories are also taught giving students a vast background on design methodology subjects. The paper concludes that theories behind a design process are not widely taught on the contrary to design methodologies which are widely taught in an academic background less close to the reality of industrial application. Tomiyama reasons this gap by the lack of innovative design. Also in industry the majority of the designs are routinely improved making a design methodology which follows steps for a new product design less useful. The team also identified insufficiencies of the current DTM which opens the door for future research topics. The considerations focused on increasing of product complexity and multidisciplinary,

as well as having multiple stakeholders with different cultural and educational background.

The train front cab cleaning design process project addressed such insufficiencies that were faced by the design team. The gaps identified by Tomiyama [16] were highlighted during the observations and analysis that were conducted as part of this research.

2.3.1 Robotic Design Process

A robotic design process is similar to any design process that follows a systematic sequence of more than one engineering discipline. The design process can be split into three design areas mechanical, electrical, and software as shown in the design process example of a gripper robot in Figure 8. Each discipline has its own process and standards which the design is based on. At the end of the individual design stage, designed components are integrated and tested

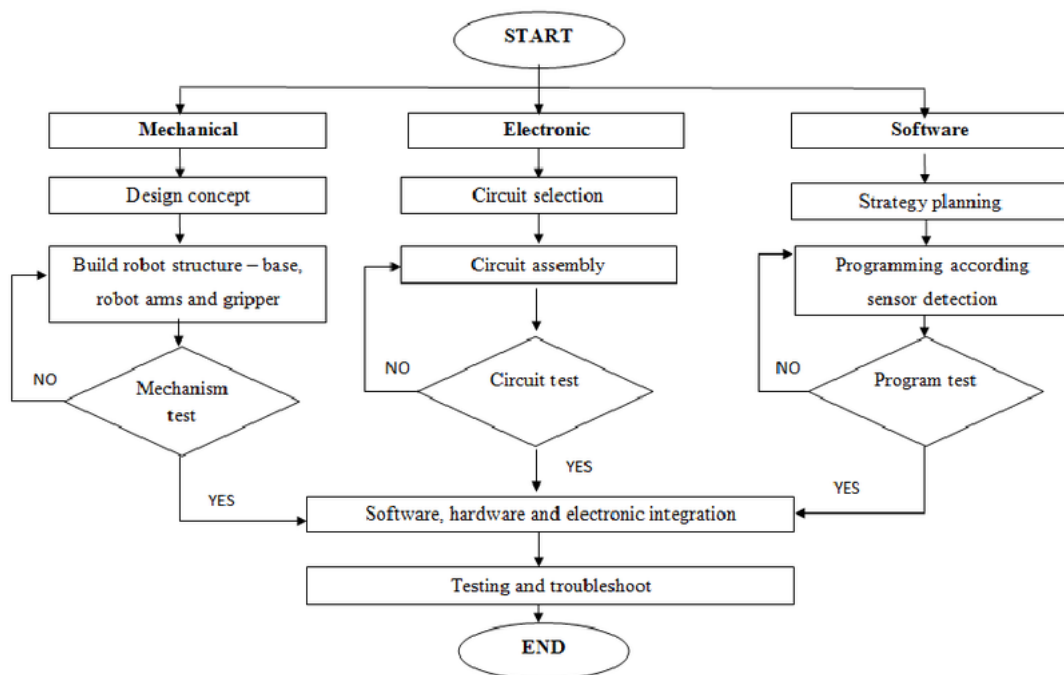


Figure 8 Flowchart for the development of a gripper robot [17]

2.3.2 Systems Engineering

Systems engineering (SE) is an interdisciplinary approach which means to enable the realization of successful systems [18]. SE aims to define customer needs and necessary functionality at early stages in the design development process. The structuring of a development process includes all engineering disciplines in one effective team, taking the project from a concept to operation.

Systems thinking sharpens the awareness of wholes and how the parts within those wholes interrelate, it was described that systems thinking occurs through discovery, learning, diagnosis and dialogue that lead to sensing, modelling, and talking about the real world to better understand [19].

There are many SE process representations followed by the industry. One of the most common representation is the V- model shown in Figure 9, this model summarises the steps that need to be taken to fully develop a system engineering design. The project definition describes the decomposition of the requirements and definition of the system specifications. The project test and integration represents the integration of the whole systems and validations of the results.

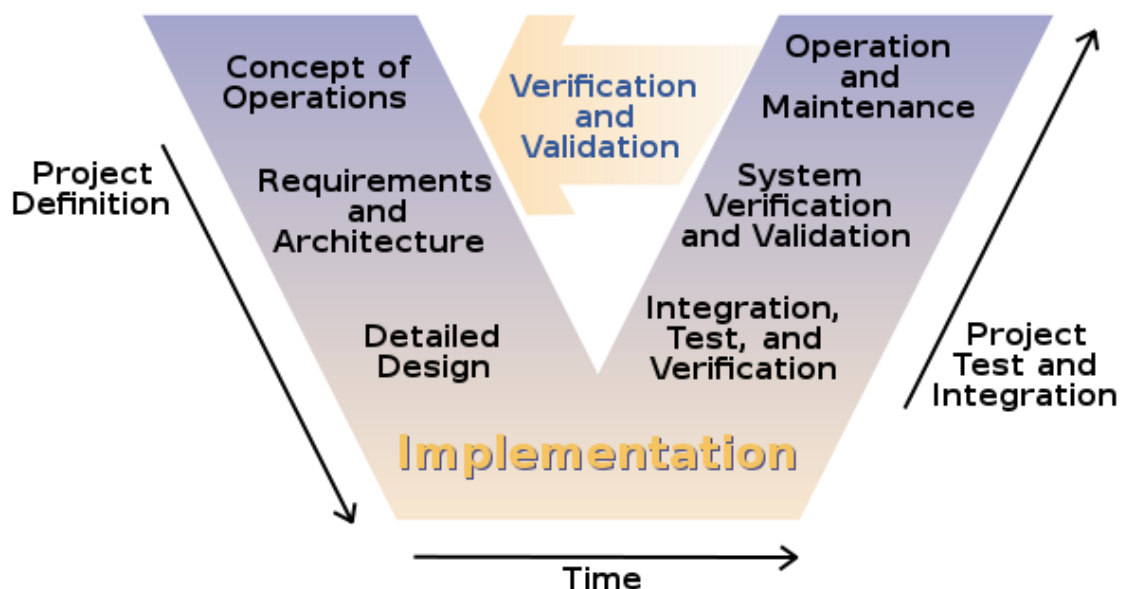


Figure 9 Systems engineering process development V-model

3 METHODOLOGY

In this section Six Sigma Define-Measure-Analyse-Improve-Control (DMAIC) [20] methodology will be described and applied. The DMAIC is a cyclical problem solving model that can be used to improve, optimize and stabilize a process. This thesis will cover the first three steps on the DMAIC methodology. The two remaining steps would be for further consideration.



Figure 10 Five steps of DMAIC [20]

3.1 Define

This thesis aims to describe problems during a multidisciplinary design project and analysed decisions taken which caused project delays and problems. The method used to approach this research topic was 'ethnographic' placing the observer into natural setting of the project being investigated. This approach is different from observing a case as a viewer and use questioners and surveys to collect data from participants. The ethnographic observation is time consuming but the highly detailed data that can be gathered from such observations makes it favoured among different approaches [21].

The focus of this observation was based on several measures'. First, the communication between project members from different engineering disciplines who completed common tasks and faced interface issues during the design process. The proposed Gantt chart was limited by the exhibition date set by

RSSB for the funded projects, the division of task and deadlines was created by the teams depending on their contribution time for the project.

Second, knowledge transfer between different disciplines was a key measure to account for the design process development.

Finally, the environment setting and the active timescale of participants contributed to organizational and managerial issues during the project.

3.1.1 Project Setting

The project was a collaboration between two universities Cranfield (CU) and Heriot-Watt (HWU) along with consulting partners from the rail industry Bombardier, Chiltern rail and robotics specialist Shadow robots. The sites of work were both University Campuses located in Cranfield and Edinburgh respectively.

Cranfield University was the lead in project with the following responsibilities:

- Systems design by Andraz Krslin (AZ) [22].
- Conceptual design by Luis Rubio Garcia (LG) [23].
- Mechanical design and building scaled model prototype, system integration and testing by Gerard Taykaldiranian (GT).

Heriot-Watt University joined covered:

- Control implementation by William McColl (WM) [24].
- Vision based detection by Connor Mann(CM) [25].
- Force control application by Joao Moura (JM) [26].

The consulting partners provided industrial insight such as the depot visits, data such as CAD train cab model and train clean procedures and cab front statistics [22][23] Appendix A. Market sensitive information was not included in any report

3.1.2 Participation and Work Sequence

The project officially started in May 2016 with 4 participants the other 2 joined later as can be seen in Figure 11.

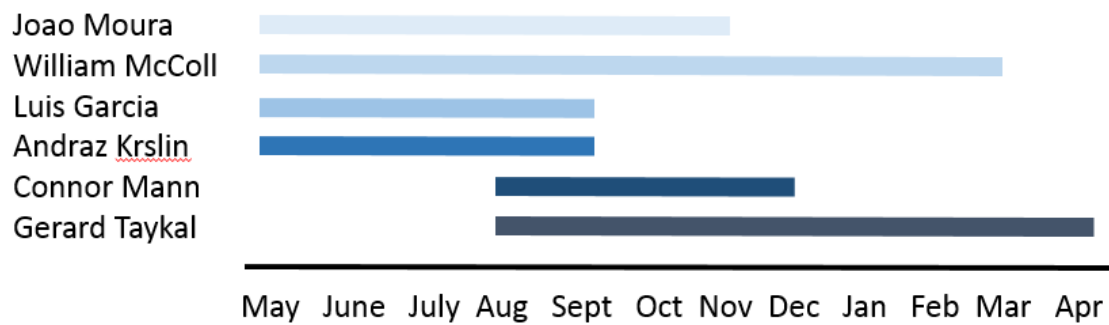


Figure 11 Individual participation during design project

The sequence of the project tasks depended on when the team members were assigned to the project, whether by individual projects or as part of their Master's by research. Therefore the sequencing of the tasks was uncontrollable. Some tasks were done in parallel but in different locations as shown in Figure 12.

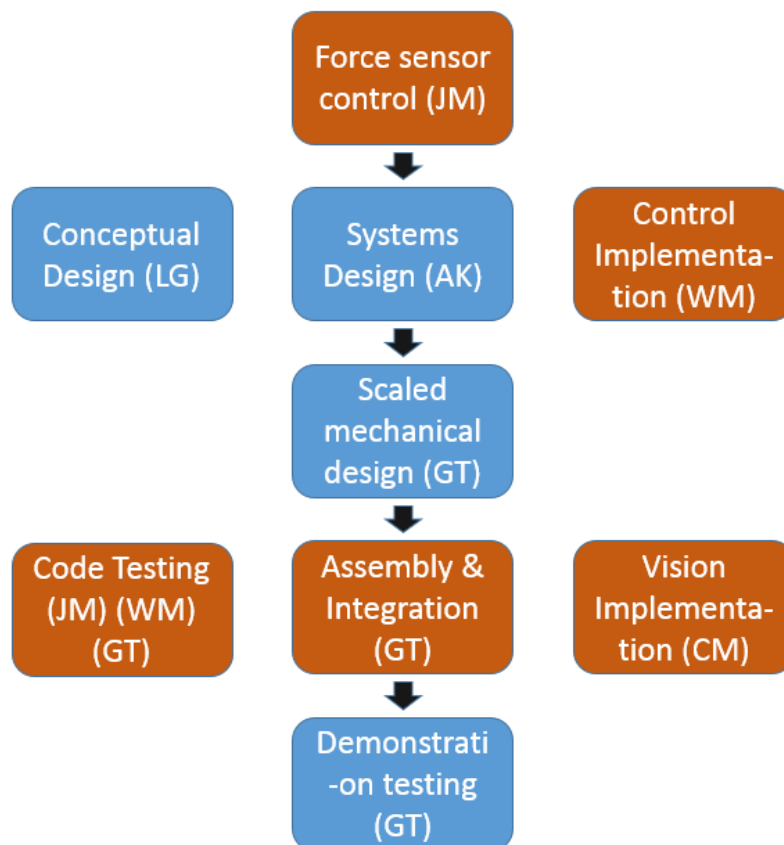


Figure 12 Sequence of the design tasks blue in CU, Orange HWU

3.2 Measure

For data collection, design activities from the “Train cab front cleaning robot” project were used. To simplify the process, the project Gantt chart proposed was compared to the actual time taken for the tasks to be completed. This allowed to narrow down the areas of particular interest in delay cause. Using the Gantt chart to map activities such as workshops, skype meetings, project deliverables, e-mails, milestone sponsor meetings, key decisions and processes were highlighted.

Two templates were used to track the project progress activities. Meeting minutes were used for workshops and skype calls between Heriot-Watt and Cranfield University. A monthly formal report found in Appendix E was sent to RSSB which included:

- Deliverables progress and deadlines
- Monthly key achievements
- Delays, challenges and risk
- Implementation/collaboration opportunities
- Change recommendations
- Assistance or requirements
- Planned activity coming up
- Updated project Gantt chart

The challenges and issues were examined based on the outcome of the reports showing the project progress.

3.3 Analyse

The aim of analysing this project was to produce a descriptive observation of the design process to identify decisions and key actions which caused the delays and problems in the project.

The identified issues will be classified into four categories External, Managerial, Design and Logistical. A cause and effect analysis was used to categorize the

issues in terms of three effects; increase in cost, delay in project schedule and affect the quality of work.

4 DESIGN PROJECT

4.1 Introduction

The use of autonomous systems in manufacturing and maintenance engineering processes is increasing with the development of new technologies and demanding market needs. Rail passenger journeys reached 1.73 billion in the last 12 months [27] and are expected to increase over coming years as shown in Figure 13.

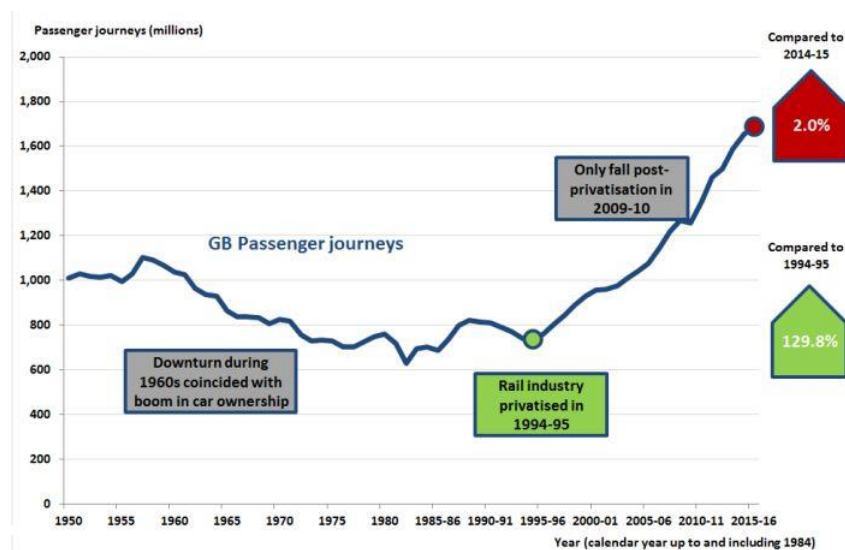


Figure 13 Number of passenger journeys with respect to years from 1950 to 2016 [27].

This increase in demand will have an impact on current infrastructure and total fleet numbers, meaning that new depots will be needed and current depots will have to add more trains to their already busy maintenance schedules.

Cleaning the exterior surface of the train is one of the tasks that is scheduled in maintenance depots. Although the body side panels of the train are cleaned using an automatic mechanical washer Figure 14, the front of the train cab and gaps between carriages are excluded from this procedure. Manual labour is used to clean the front of the train cab Figure 15, whereas the gaps between carriages are cleaned less frequently due to difficulty of the task. However, complying with the health and safety requirements in environments that contain high voltage rail

or overhead lines presents a number of practical obstacles for efficient cleaning methods. While the cleaning sequence usually involves the rinsing of the train, before brushing and then rinsing again, cleaners do not duplicate their exact motion for every train. Variations in manual cleaning methods, combined with elementary cleaning equipment and other challenges associated with access to the train due to depot layout and obstacles means cleaning results vary.



Figure 14 Left: Electric train side wash Willesden depot, London. Right: Diesel train side wash Wembley depot, London.



Figure 15 Left: Manual cleaning of diesel train Wembley depot, London. Right: Manual cleaning of electric train Willesden depot, London.

The increased complex shapes in high speed trains shown in Figure 16, and the risks rising from manual washing encourage the study of a flexible and inexpensive robotic and autonomous system (RAS) that can clean the front cab of the train. From this rising challenge Cranfield University won funding of the project in partnership with Heriot-Watt University, Bombardier Transportation, Chiltern Railways, and Shadow Robot Company, by the railway Safety and

Standards Board (RSSB). The aim of this project is to prove the concept of a train cab front cleaning robot by designing and demonstrating a functional prototype capable of recognizing the surface and generating a path plan with a constant force applied on the surface to ensure cleaning efficiency. The autonomous system should reduce cleaning time and make the task safer by eliminating health and safety hazards.



Figure 16 High speed trains front cab shapes [28].

Cranfield University's main role is to provide the systems and mechanical design of the robot. One of the main challenges to solve is integrating the control system designed by Heriot- Watt University with a mechanical system that is capable to sweep complex 3D surfaces using minimal workspace in which the robot will be operating.

This master thesis will focus on ending the first stage of the train front cab cleaning feasibility study project by integrating the system, mechanical, and control software designs to develop a functional scaled prototype. Additionally, this thesis will cover observations from a multidisciplinary design project environment to identify problems encountered during the development process. The goal of such observation is to highlight academic challenges in industrial type projects.

The project involved in this thesis was a feasibility study of a new product. A new product development process is a series of interdependent and frequently overlapping activities that transform an idea into a product ready to be marketed [29]. The process is flexible and always refined for technical and commercial feasibility. Nowadays, manufacturers are growing a new trend of giving initial specifications of some components for suppliers who will continue the engineering process and provide the manufactured component at the end. Kawasaki in the 1980s started outsourcing the seats by giving the specifications to suppliers [29]. This can turn the focus of engineers into more sophisticated design tasks. This can be an important factor in the product development of the train front cab cleaning robot due to the fact of limited numbers of specialists working on this project. Figure 17 shows the product development cycle for the project and the phases in the red box were part of the work done by the author. This will make it clear to the reader to understand the process followed, and will categorize the work by all the designers who participated in the development of the train front cab cleaning robot.

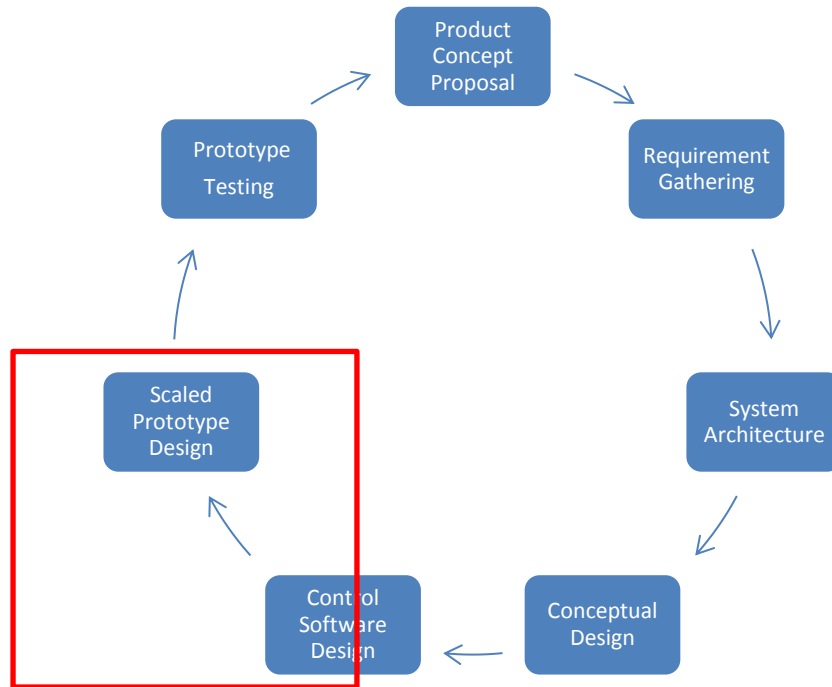


Figure 17 Product development cycle for the front cab cleaning robot.

Figure 17 highlights the work done by the author which focused on integrating the systems and building a functional scaled model of the robot for demonstrating the capabilities of the design. The core of this research was to observe the design and development plan, by using data gathered throughout the design process the multidisciplinary project was analysed to pin point the gaps and challenges that rise from such projects within academic research.

In order to put the reader within the scope of the project, different tasks and designs done by the team are summarised in the sections below. The focus of this thesis will be concentrated on the communications and ability to transfer the knowledge between various design teams.

4.2 Product Concept Proposal

The concept was proposed by Professor Tomiyama from Cranfield University to RRUKA as a feasibility study for a competition in “Applications of Robotics and autonomous Systems to Rolling Stock Maintenance” [30]. The proposal contained a full description of the project in terms of aims and objectives, methodology, draft concepts, project plan, and cost justification. The proposal was chosen among four other projects under the same competition title to apply a feasibility study as a starting stage.

4.3 Requirement Gathering

The project was defined in the proposal as a concept. To start building up information about the design, knowledge had to be gathered and shared between the project partners. Visits were conducted to partner's maintenance depots where the manual cleaning procedures were examined. The reports from the visits were written by Garcia [23]. Kršlin [22] organized and arranged all the requirements in a Set Based Concurrent Engineering (SCBE) method of Key and Secondary value attributes. Each attribute represented the key concerns of the robot design. A summary of the conducted visits and requirements gathered can be found in 7Appendix A.

4.4 System Architecture

The third stage of the process involved identifying and designing the system architecture which was done by Kršlin [22]. A Function-Behaviour-Structure (FBS) approach to function modelling was used. This approach provided an overview on subsystems and an early indication of the expertise required for final development. Individual functions were then grouped into subsystems. While the understanding of systems architecture is important, the design has to operate in a real environment. Following the SBCE approach by Kršlin, non-feasible regions of design space were identified using trade-off curves comparing conflicting or important requirements. Close cooperation between researchers meant that some subsystems could be developed concurrently, which provided additional insight into the final feasibility of the design and its limitations.

Table 1 summarises the variables and operations determined by Kršlin from the system design. The number of arms were decided based on the symmetrical shape of the train. Having two arms will speed up the cleaning process, it also means that the arm reaching the train surface will be half the size of having a single arm resulting in less structural design complexity that would be needed to support the one arm configuration that can get as long as 3m to be able to cover the full width of the train from one side. One end effector per arm was enough to meet the time required to finish cleaning the train front cab which was set by the industrial partners to target less than 5 minutes. The end-effector size which was designed to be a rotating brush by Garcia [23] was set to have a diameter of 30cm in order to be able to clean the gaps between two carriages and minimal gaps on train front cab surfaces. The cleaning velocity range was chosen to match the current manual cleaning performance of around 5 minutes per front cab.

Table 1 System design variables and operations summary [22].

Variables	Quantity		Derived from
No. of Arms	2	[/]	Train shape design
No. of End effectors per Arm	1 or 2	[/]	Pareto analysis
Size of End effector brush	0,3	[m]	Minimal gaps
Velocity of End effector on surface	0,4 to 0,65	[m/s]	Current performance
Tolerance on brush path	0,05	[m]	General recommendation
Velocity of End effector retracting	0,65	[m/s]	Equals max. velocity
Operations	Solution		Derived from
Cleaning sequence	J sequence		Duration vs. effectiveness
Base Design	X1		Performance vs. Cost, Base compatibility
Detection design	RFID, IR array & Laser surface velocity-meter		SOA, Cross requirements evaluation
Depot Placement	Installation with current side cleaning plant		Operation benefit, Cost

4.5 Conceptual Design

This phase of the development process started with applying the sets of requirements of the design found in Appendix 7A.2. Usually more than one conceptual sketch is considered. The conceptual design of the train front cab cleaning robot was done by Garcia [23]. During the workshop that was organized between Cranfield and Heriot-Watt Universities the concepts developed by Garcia were discussed and one design was chosen to continue further development. The four designs will be discussed briefly in this section in order for the reader to capture the key points that led to choosing this type of mechanism for prototyping and later on detail designing the full mechanism.

The four conceptual designs shown in Figure 18, were considered against a set of specifications

- Stopping the train at a precise position is difficult. This means the design must be adaptable to a change of $\pm 0.5\text{m}$ in the train's stopping position. This figure was given during the system's discussion with the industrial partners.
- The design must be able to clean gaps in between the carriages. This is a narrow area of around 30cm, meaning that the mechanism has to fit within this area and avoid colliding with the train carriage.
- The robot must have a simple control system and mechanical structure to meet with the low-cost requirement.

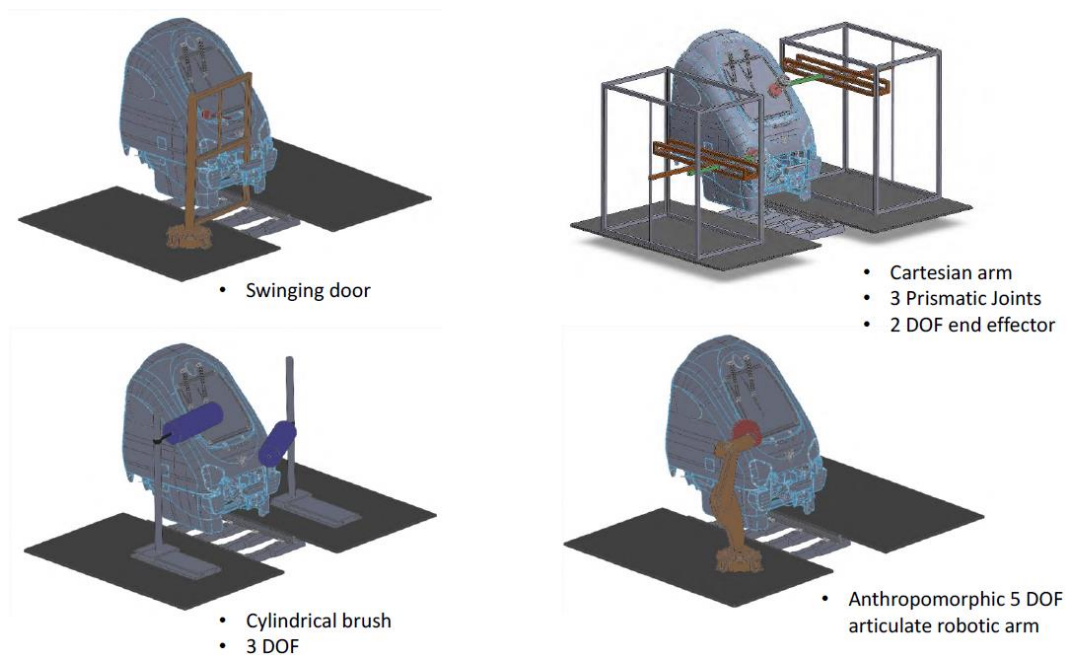


Figure 18 Proposed conceptual designs during the workshop held in Heriot-Watt University[23].

The swing door design was relatively complicated for the cleaning task and had no margin of error for the train stopping position. Cleaning in-between the gaps of carriages was not an option with this design since the doors would not be able to close.

The cylindrical brush design does not have the ability to adapt to the error of train stopping position. Moreover, cleaning using the cylindrical brush will not be as effective as the cleaning done by smaller rotating brushes that are able to target smaller areas with complicated surfaces more efficiently.

The anthropomorphic arm would require a large working space due to the awkward arm movements that the robot will use in order to clean the surface. Most importantly the control

system of such robots would be complicated since different inverse kinematic solutions can be generated for the same position. This problem was seen in the testing of the control software on the Baxter robot performed by Moura [31].

The Cartesian arm consists of four DOF: with three prismatic joints used to position the end-effector in a XYZ Cartesian space, and one passive DOF added to the end-effector brush helping it to adapt to different surface curvature. The Cartesian motion allows the design to cover the surface accurately, with a simple control system compared the other mechanisms such as robotic arms. This design will also be capable of adapting to the margin of error regarding to the stopping position of the train and uses a minimum workspace between all the proposed conceptual designs.

4.6 Control Software

The control software was designed by Moura [26] from Heriot-Watt University, his work provided the control and path planning for sweeping an unknown 3D surface using a robotic manipulator and a force sensor attached to the end-effector. The force sensor measured forces and torques reacting on the end-effector, using these readings the code kept the force roughly constant and the end-effector oriented perpendicularly to the sweeping surface. The algorithms were implemented in Python programming language which is supported by Robotic Operating System (ROS). ROS is a framework for writing robotic software which supports a selection of equipment such as sensors, actuators, and robots. ROS runs mainly on Ubuntu Linux operating system.

The Hardware used to initially test the software was a Baxter robot which has 7 degrees of freedom arms, a force sensor that measures forces and torques in the x, y, and z directions. A soft 3D surface was used for testing and the end-effector used for the experiment consisted of a smooth sponge to interact with the surface.

The control model sweeps an unknown 3D surface, this is of particular interest to the project where the cab front cleaning robot arm has to sweep the front surface of the train cab making it adaptable to any front cab shape. This was achieved by using the information from the force sensor

The contact to the surface was maintained automatically by commanding the robot end-effector to translate along the direction to approach the train till a force reading was achieved by the force sensor. Once a contact in the direction perpendicular to the train surface is achieved, the cleaning motion starts on the surface. A rough idea of how much space was covered by the cab front in the perpendicular plane x-y dimensions was estimated, because the width of the trains are fixed or at least similar. Therefore, the movement in the x-y plane considering the width of the train front was planned, and then projected it to the actual surface by compensating for the variation of surface curvatures in the z direction. This approach can be represented by the drawing in Figure 19, where a pre-planned raster scan can be seen on the x-y plane Figure 19 (a) and its projection on a non-flat surface Figure 19 (b). Please note that the projection on the non-flat surface was not pre-computed; this projection occurs automatically in the run-time because the robot automatically compensates the variations in the z direction while following the path pre-planned in the x-y plane.

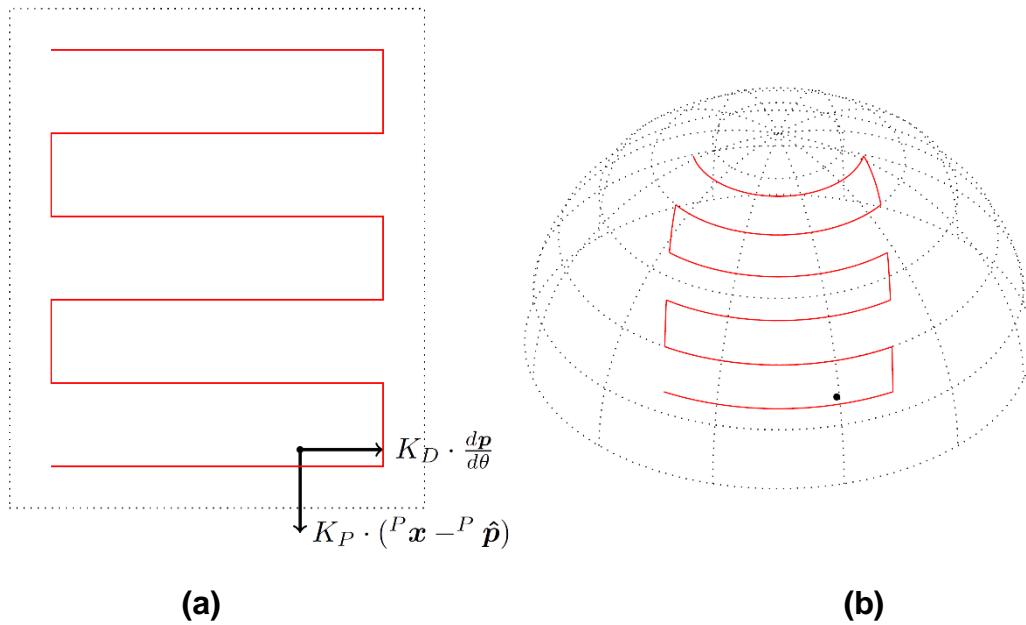


Figure 19 (a) surface scan path planned on a flat surface. (b) The surface scan path projected onto a non-flat surface.

The desired end-effector speed (\dot{x}_d) to be fed into the controller was generated by considering two things: the iteration throughout the pre-planned path in the two dimensional x-y hypothetical plane and the corrections of the deviations from this pre-planned path. Both factors were

generated using proportional coefficients, K_D and K_P , respectively, where K_D controls the speed along the path and K_P keeps the end-effector along the path by generating a perpendicular speed proportional to the amount of the deviation.

4.7 Mechanical Design

The goal of the project was to successfully integrate the designed components of the train cab front cleaning robot and through the process of integration the design development of an academic project was observed leading to the identification of many project issues that led to problems and delays. This chapter defines the steps taken in order to achieve the system integration and build the 1/8th scale model of the robot. Additionally the observations process of the overall designs and team participation was addressed.

4.8 Prototype mechanical design

The mechanical design will provide the structure for the control software to accomplish the required task of cleaning an unknown 3D surface. The design has certain specifications and parameters that need to be taken into consideration. In order to prove the concept of train front cleaning robot a 1/8th scaled prototype was developed due to budget and time limitations, therefore the components that were selected for the prototype had to match the design of the full sized model.

The conceptual design provided by Garcia [23] was reassessed and the following parameters were set to start the prototype design:

Functionality: The robot must perform better than the manual cleaning process of the train cab front which is currently done in UK depots. The degrees of freedom (DOF) needed will allow the robot to cover any type of 3D surface within the limits of the end-effector dimensions.

Reliability: The robot must replicate the action of cleaning with a constant force application in a smooth manner. The quality of manual cleaning is not the same as it is impossible to have an efficient cleaning throughout the process due to human factor restrictions. Introducing the cleaning robot will allow a homogenous cleaning process by applying a constant cleaning force on all the surfaces..

Motion Range and Speed: The range of motion has to be calculated for each joint allowing the end-effector to cover the application area in full. The speed of the joints are restricted to the

motion of the end-effector speed on the cleaning surface. The end-effector was set to complete a full surface clean within five minutes this parameter was set as a requirement from the industrial partners.

Weight: The weight of the end-effector must be optimized to the smallest weight possible. This weight will have an important effect on the structural design of the robot and will play a key role in vibration and jerk.

The conceptual design of the mechanism consisted of a Cartesian XYZ motion with passive end-effector attached to the extruded arm as described in previous sections and shown in Figure 20. From the system design Krzlin [22] and conceptual design Garcia [23] it was noticed that having one arm sweeping the full surface of the train adds structural design complexity due to the length that would be installed (3m long). It was also calculated that the speed of the end-effector had to be high compared to having two identical arms each cleaning half the side of the train front cab.

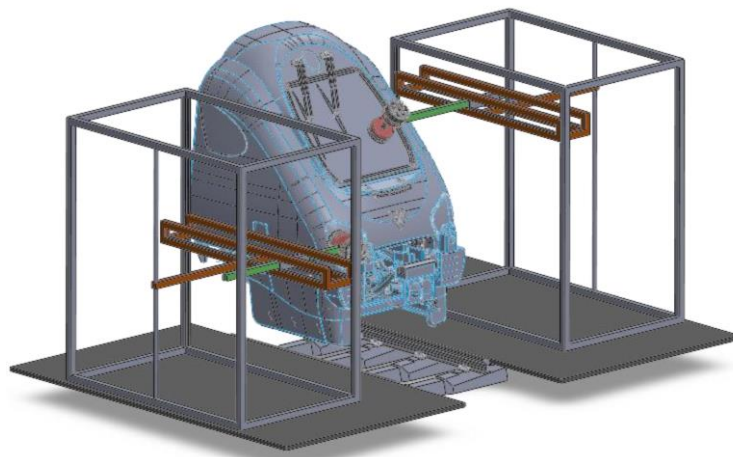


Figure 20 Conceptual design by Garcia [23]

4.8.1 Prototype

One of the main deliverables of this project was a functional prototype that concludes the feasibility study and allows to take the project to the next phase of building a full sized robot.

Since such robotic applications were relatively new, it was challenging to find a low cost mechanism that can fit the needs and requirements of the cleaning robot [12]. It was also important to have a prototype built from the same components that would be used for the full

sized robot. This will help in testing and optimizing the design before going to the next phase of development.

4.8.1.1 Gantry system

The gantry system Figure 21 , provides a wide range of applications such as pick and place, measuring, handling, assembling, and identification in microelectronics/medical technology. This system comes with a lot of benefits that suit the needs of this project from low maintenance features, and simple construction of configurations that meet the requirements.

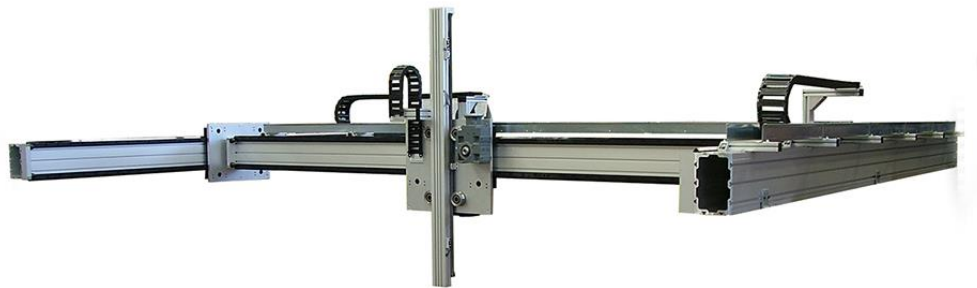


Figure 21 Industrial XYZ gantry system from HepcoMotion [32]

Gantry units are made of high profile aluminium anodized rails that drive carriages using various options including belt, ball screw, and rack and pinion. From looking at the robot dimensions and the speeds needed for operation the most suitable type of driver was the belt driven mechanism shown in Figure 22 , that has a position accuracy of ± 0.2 mm, maximum speed of 5 m/s and can carry loads up to 500 N [33].



Figure 22 Belt driven carriage gantry unit [33].

After choosing the mechanism type, initial calculations were made to decide which belt driven gantry to use. Two companies that provide gantry solutions Igus and HepcoMotion were consulted. Each type of gantry unit data were provided on the company's web pages [33][32], and were organized in Table 2 below. In order to choose the right gantry unit initial deflection

analysis was made to check which unit will have a maximum deflection of less than 2 mm [33][32] which is the maximum deflection recommended by the companies for normal operation of the carriages on the gantry rails. The following beam deflection formula was used [34]:

$$\delta_{max} = \frac{Pl^3}{3EI} \quad (4.1)$$

Where,

δ_{max}	Maximum deflection
P	Load applied (40 N in Y and 35 N in Z)
l	Length of the beam (1.72 m)
E	Modulus of elasticity of the material (70,000 MPa)
I	Inertia

Table 2 gantry properties and initial deflection calculations.

Product	Inertia, I _y	Inertia, I _z	weight	load	speed	max stroke	Max defl. Y	Max defl. Z
	m ⁴	m ⁴	kg	N	m/s	mm	m	m
ZLW-1040	9.756E-08	5.491E-08	3.24	300	5	2000	0.008692852	0.02647682
ZLW-1080	4.83653E-07	8.6613E-08	3.24	300	5	2000	0.001753478	0.0167855
ZLW-1660	5.40876E-07	7.73489E-07	12.6	500	5	3000*	0.001567965	0.00187959
PDU2	6.13333E-07	2.93333E-07	7	500	6	6000	0.001382731	0.00495629

The loads applied in Y (perpendicular to the cleaning surface) and Z directions are the forces needed to clean and the estimated weight of the end-effector respectively. The cleaning force was calculated from the test results that are found in section 4.11.1. The estimated weight of the end-effector can be found in Table 10 in 7Appendix B.

The results calculated in Table 2 show that only one gantry; unit ZLW-1660 meets the deflection requirement. The dimensions provided in Garcia's conceptual design were scaled down to 1/8th the original size

Table 3

Table 3 1/8 scale prototype information.

Gantry unit	Length	without carriage	weight	1/8 scale	1/8 weight
ZLW-1660	mm		kg	mm	kg
Vertical Gantry	1720	1600	23.35	200	0.98
Horizontal Gantry	3120	3000	19.6	375	1.225
End-effector Gantry	3870	3750	12.6	468.75	1.35625

4.8.1.2 Scaled model

The first prototype of the model had to be delivered within one year of the project time scope. The dimensions provided by Garcia [23] were scaled down to 1/8th the original size and the components were first assembled in CATIA as shown in Figure 23. This CAD model was used to validate the dimensions and also to calculate the joint positions accurately for the control system.

Part of the demonstration plan was to test the ability of the robot to sweep a solid 3D surface of a train front cab. The cab CAD drawing was provided by Bombardier transportation was scaled down and the surface model was converted into a solid which was modelled using a CNC machine. Some details found on the front cab such as wipers handles, and headlights were extracted as well and 3D printed to be added to the solid model of the train front cab.

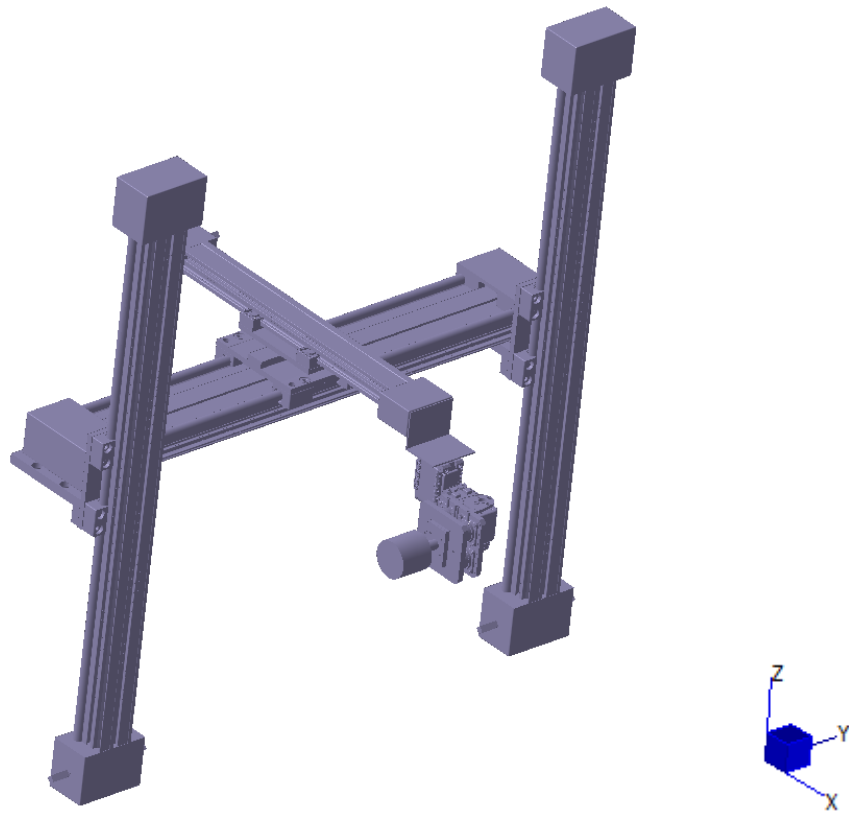


Figure 23 Detailed CAD model of the scaled Robot.



Figure 24 1/8th scaled model of train front cleaning robot during RRUKA event at the Science Museum in May 2017

4.9 Initial Finite element Analysis for full scale rail beams

Finite element analysis (FEA) was done for the rails and joint of the gantry system. The geometries were imported from the supplier to CATIA and solid model were created based on the full scale model. The aim of this analysis was to check for the displacements of the rails due to bending.

Strand7 was used to analyse the rail beam displacements and bending moments of the robotic gantry arms. The cross section of the rail in Figure 25 was imported from CATIA as an IGES file to have an accurate calculation of the Inertia.

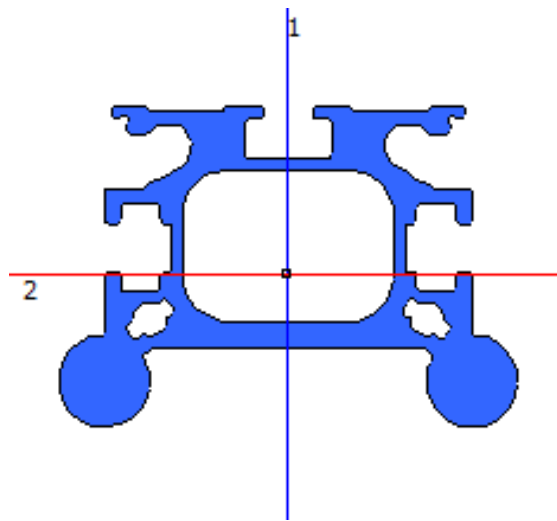


Figure 25 Rail Cross section for finite element analysis.

The three beams are analysed separately and the reaction forces and moments were calculated first from the extended end-effector arm and used for the next gantry rail respectively

All three gantry rails were assigned beam elements of their specific length, then they were meshed using the sub divide tool creating nodes along the length of the beam. The cross section in Figure 25 was assigned to the beams and the structural properties of Young's Modulus and Poison's Ratio were added 70,000 MPa and 0.3 respectively.

The weight of each rail was calculated as shown in Table 4, by using data provided from the supplier [33] more detailed calculation can be found in Table 10 in 7Appendix B.

Table 4 weight and length of each gantry unit.

Gantry unit	Length	weight
-------------	--------	--------

ZLW-1660	mm	kg
Vertical Gantry	1720	23.35
Horizontal Gantry	3120	19.6
End-effector Gantry	3870	12.6

Table 5 shows the beam elements nodes which are created at the ends of the beams and for the horizontal gantry an extra middle node was added. Each gantry was placed in position where the loads will have the highest effect. Both carriages of the vertical and end-effector gantry are placed at their extreme ends. Whereas the horizontal gantry carriage is placed in the middle where the largest sag is predicted.

Table 5 Initial forces, moments, and constraints of nodes.

	Fx	Fy	Fz	Mx	My	Mz
	N	N	N	N.m	N.m	N.m
Vertical Gantry						
Node 1	Fixed					
Node 2	0	43	-35	0	0	0
Horizontal Gantry						
Node 1	Fixed					
Node 2	0	35	155	0	-62	-73.96
Node 3	Fixed					
End-effector Gantry						
Node1	-35.56	17.5	-75.5	-60.45	30.877	-18.49
Node 2	Fixed					

The same axis shown in Figure 23 was used for all 3 models in order to simply transfer force and moment inputs without the need for changing signs or axis.

End-effector Gantry was fixed at one end and two forces were applied on the other end. The first was the cleaning force in the FY direction and the second was the estimated weight of the end-effector in the FZ direction. Using linear static solver the reaction forces, moments, and displacement are calculated. These forces and moments are used as input data for the horizontal gantry

4.9.1 Finite element analysis results

The purpose of this analysis is to compare the calculated stresses and deflections with the allowed figures of the material used or design criteria. All structural components must be designed to operate on loads greater than the expected during the operation of the robot. This

section will provide the critical results that needed to check for the normal operation of the robotic arms. The three gantry rails were analysed to get the acting stresses and max displacement of each gantry. In this design case the loads applied are small with respect to what the structure can handle. However, the critical point is the allowed displacement of no more than 2 mm in the rails. A displacement more than 2mm will effect the quality of the carriage translation over the rail which might lead to the jamming of the system resulting in a damaged carriage of rail as well as the motors from excess torque generation.

Figure 26 below show the maximum displacement of 1.01 mm on the end-effector rail gantry. This displacement occurs when the gantry is fully extended leaving a margin of around 50% before reaching the maximum allowed displacement.

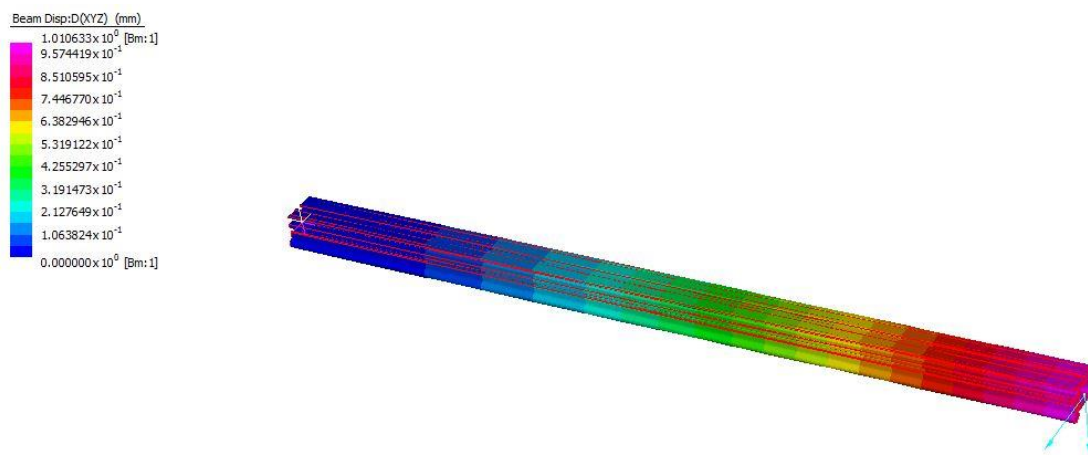


Figure 26 End-effector gantry rail displacement

The highest bending stress of 2.19 MPa occurs at the fixed joint of the gantry when fully extended. This stress is very low compared to the yield stress of Aluminum which is around 95 MPa.

The horizontal gantry rail analysis resulted in a maximum displacements of 0.47mm as shown in Figure 27. This displacement is less than the maximum allowable sag of 2mm.

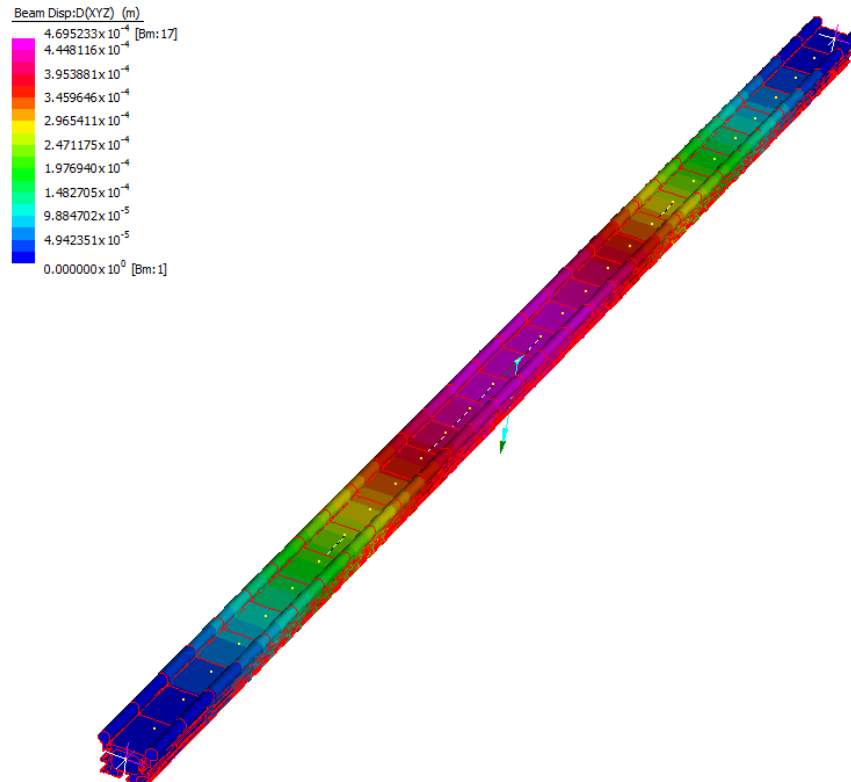


Figure 27 Horizontal gantry rail displacement.

The results from the vertical gantry do not comply with the allowable displacement. The calculated displacement was 6.47mm three times more than the allowable as shown in Figure 28. This leads to the need of adding an extra support beam that will fix both vertical gantries as this is critical for the carriage operation on the rails.

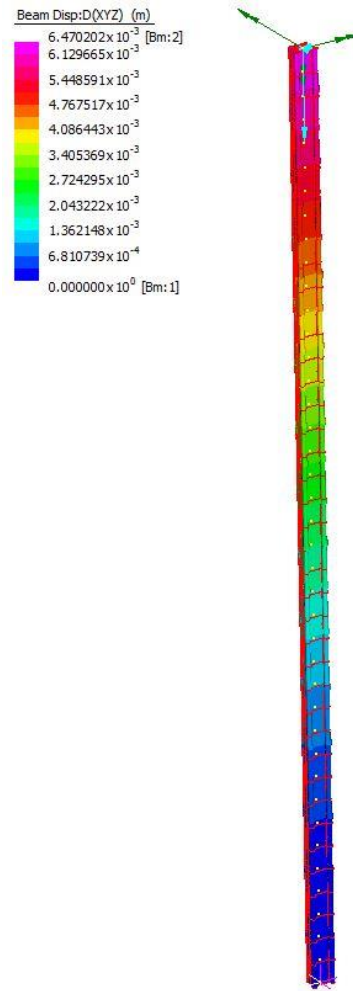


Figure 28 Vertical gantry rail displacement.

4.10 Integration

The robot was designed by different designers, during different time periods, and in different geographical locations. During the integration period three out of the five engineers who were working on the project had finished their designs and were no longer participating in the project. This factor increased the difficulty of the integration process.

Many issues were faced during the integration phase of the scaled prototype. Dealing with multidisciplinary design team is an industrial challenge which is not usually the case for academic projects that take place in Universities. During the process those issues were tackled and solved according to available knowledge.

In order to integrate the designed systems and have a prototype which is functional and ready for testing, key procedures and designs were taken from the fellow engineers who worked on specific design challenges

Systems design gave a general knowledge of the overall system to be manipulated recognizing the key components and the process that was needed to be followed for achieving the goal of this project.

The conceptual design of the mechanical components were used as a starting point for picking the most suitable parts for the required tasks of the demonstration model of the robot.

One of the most difficult tasks was preparing the designed control software to be integrated with the prototype robot which was built using a different robot platform on which it was designed and tested.

4.11 Testing

The robot was assembled and tests were conducted by running the robot's end-effector on two different 3D solid surfaces. During the initial tests, a half cut plant pot was used; to compare the test results with the ones conducted by Moura [26] on the same pot using the baxter robot when developing the control system. The other 3D surface used was the scaled front cab surface of a Bombardier train which was modelled for the purpose of demonstration. The two surfaces were used for testing and calibration of the robot.

4.11.1 Force Analysis

The force applied needed to clean the front cab of the train was estimated from the following test. A car with a large front surface area shown in Figure 29 (A) was hired and driven for a long distance to collect dirt and bugs, and the front surface was cleaned by using a brush similar to the ones used in the depot as shown in Figure 30. The force sensor of Figure 31 was connected to the brush in order to register the forces applied to the cleaning surface and compare different forces to the cleaning quality achieved.



Figure 29 Hired Van to simulate the front cab of the train.



Figure 30 (A) Brush connected to a force sensor. (B) Brush that is used for manual front cab cleaning.



Figure 31 Force/Torque sensor from ATI Industrial Automation

Table 6 Applied brush force results

Test #	Method	Subjective Cleaning Result	Average Normal Force Applied (N)
Test 1	Soft force	Good cleaning some bugs remaining	19.93
Test 2	Soft force	Good cleaning some bugs remaining	21.07
Test 3	Heavy force	Good overall cleaning	Error in data. Brush misaligned
Test 4	Heavy force	Good overall cleaning	42.88
Test 5	Heavy force	Good overall cleaning	34.13
Test 6	High zone	Good cleaning some bugs remaining	18.28
Test 7	High zone	Good cleaning some bugs remaining	19.97

The first five tests of Table 6 were applied to the van's front surface, the application soft and heavy force denotes the applied manual pressure on the brush. It was noticed that in order to have a clean surface a force of around 40 N must be applied. Lower forces couldn't clean biological stains. Tests six and seven a high reach window was used (hence the high zone method) to evaluate the cleaning efficiency of the top areas of the train is was discovered that the highest forces registered were around 20 N which is not enough to get rid of all the dirt as shown in Test one and two where the same forces were applied.

4.11.2 Test Results

Different sets of experiments were performed to validate the functionality of the integrated systems. The experiments had to ensure that the robot is performing as expected such as the ability to keep a constant force while sweeping the 3D surface as well as keeping the end-effector perpendicular to that surface. Another test was conducted to verify that the end-effector is following a pre-planned trajectory which is projected on the 3D surface

4.11.3 Constant Force Control

The applied force was set to 10 N in the direction perpendicular to the end-effector surface. During the robot run. force data was collected from the force sensor. Figure 32 shows the force data in a graph with respect to the time. The force seems to be alternating along the 10N force with peaks of up to $\pm 2.5\text{N}$.

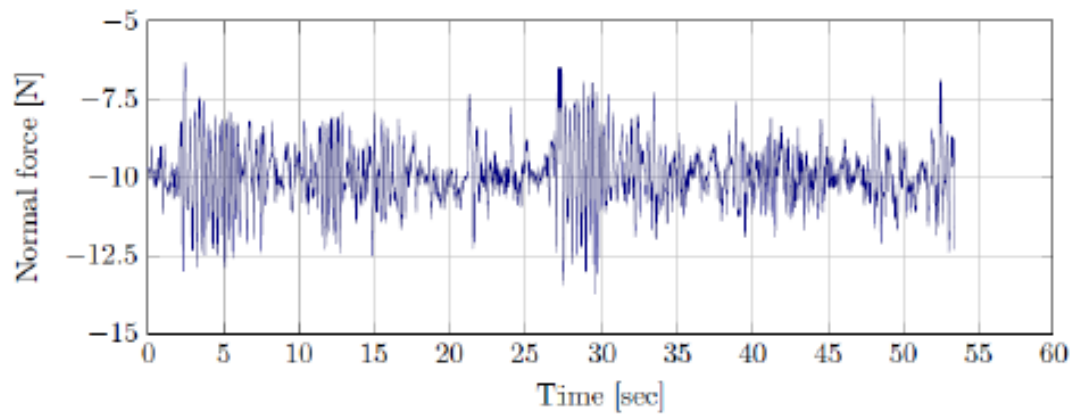


Figure 32 Normal force generated in the direction perpendicular to the 3D surface with respect to time

4.11.4 End-effector Orientation with Respect to the Surface

In Figure 33, the results of the torque readings which are tangent to the 3D surface are shown. The torque deviation is less than 0.05 Nm proving that the code is functioning and the end-effector is positioned perpendicular to the sweeping surface at all times. The variation in the torque in the X direction presents the direction of motion of the end-effector during sweeping hence the alternations in signs.

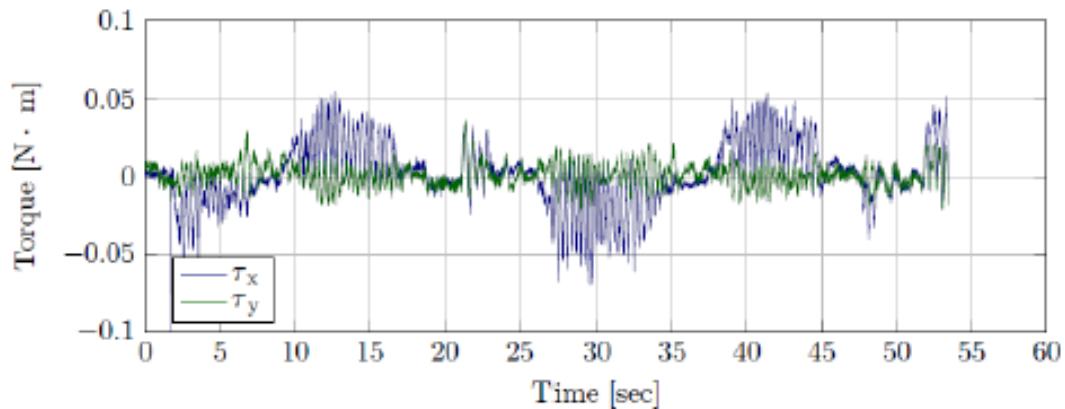


Figure 33 Torques tangent to sweeping surface.

4.11.5 Path Planning Trajectory

The first results of the path planning trajectory of the raster scan type were not promising. The robot showed very weird behaviour during the initial tests after the completion of the integration process.

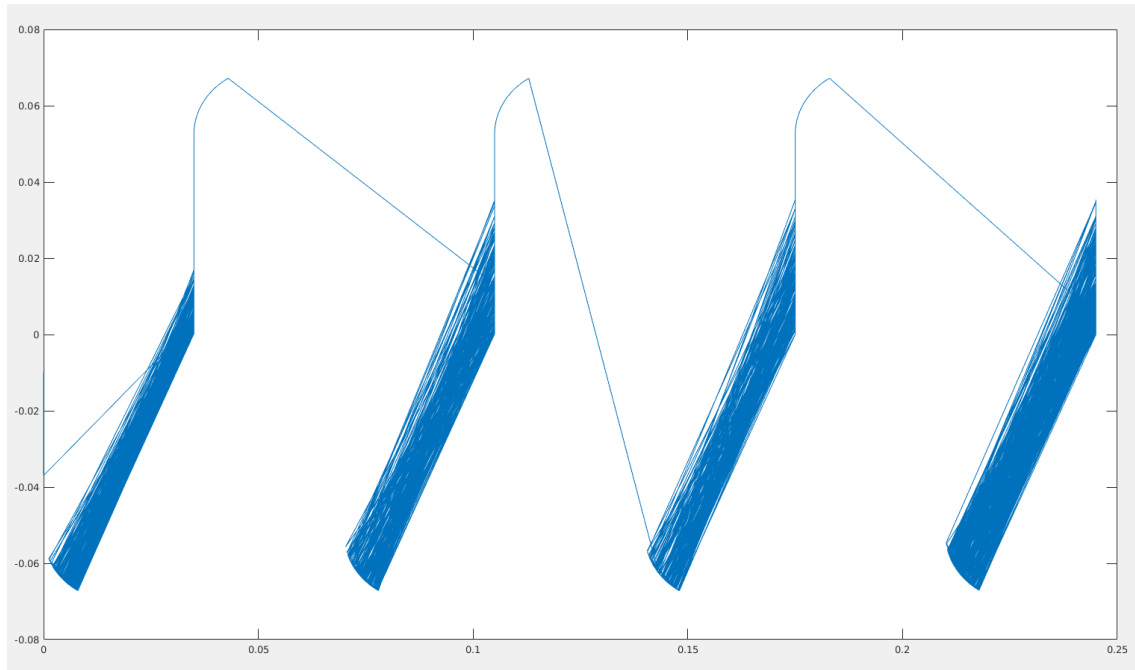


Figure 34 Initial path plan trajectory error in two dimensional graph showing x-axis and y-axis.

A ROS node was added to the code which retrieved the path plan trajectory coordinates, which were plotted on the graph of Figure 34 clearly showing the result of a bug in the code which generates the path plan trajectory.

The code was originally written on Matlab before being converted to C++. The original Matlab code was checked and the points were plotted to give a perfect raster scan. After careful examination and comparison of the codes in both languages, C++ code was refined after finding a mistake in the plotted trajectory and better results were generated as seen in Figure 35. The robot was tested and showed better output in terms of the path plan pattern, which was improved the scan quality to a point where it can be demonstrated.

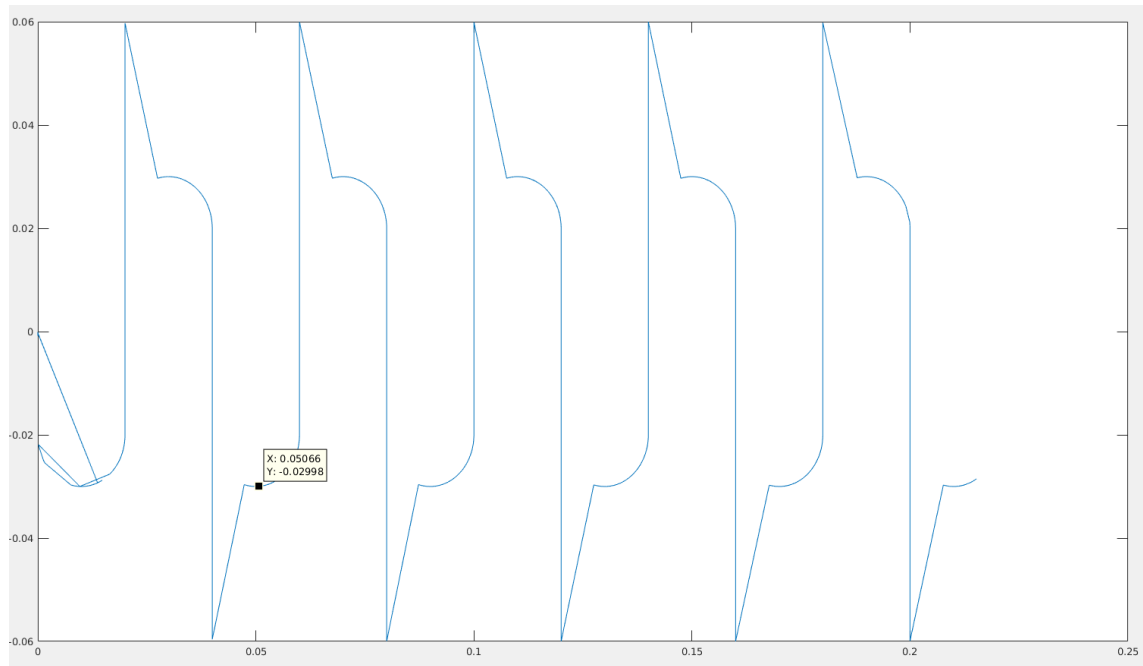


Figure 35 Path plan trajectory in two dimensional graph x-axis and y-axis after debugging the code

5 RESULTS

5.1 Project Observations

Table 7 lists the design phases with the time taken to complete each phase with the specific start-end dates in the one year project period

Table 7 Time taken in each design phase

Design	Start-end period	time
Systems design	05/2016 to 09/2016	4 months
Conceptual design	05/2016 to 09/2016	4 months
Control software design	05/2016 to 08/2016	3 months
Electrical circuit design	08/2016 to 11/2016	3 months
Prototype design	09/2016 to 11/2016	2 months
Prototype Integration	11/2016 to 04/201	5 months
Prototype testing	04/2017 to 05/2017	1 months

From the observations all the problems were pinpointed and organized into four different categories: external, logistical, managerial, and design problems.

Table 8 Categorized Issues faced during the design process

External

- Wrong Component Delivery.
- Faulty dongle used for motor troubleshooting.
- Team division between two locations.
- Project bound by external factors.

Managerial

- Absence of report templates between designers.
- Absence of design and completed task documentation.
- Team members worked during different project phases.
- Lack of communication knowledge between team members.

Design

- Poor circuit wiring.
- Implemented Control software not user friendly.
- Systems not tested before integration.
- Path planning software focused on a different type of motion.
- No standard form for integration process was planned.

Logistical

- Room allocations during workshops.
- Permission difficulties to use engineering facilities
- Software installations
- Robot transfer

Table 9 Result analysis summary for issues encountered

		Effect		
Issue	Cause	Cost ↗	Delay	Quality ↘
Wrong Component Delivery	Supplier mistake			
Faulty dongle used for motor troubleshooting	Faulty dongle			
Team divided between two locations	lack of expertise in same location			
Change / Addition to requirements	During sponsor meetings			
Absence of report templates between designers	poor decision			
Absence of design and task documentation	poor decision			
Team members worked during different project phases	poor decision			
Lack of communication knowledge between team members	Assumed common knowledge			
Poor circuit wiring	lack of time			
Implemented Control software not user friendly	Lack of time			
Systems not tested before integration	lack of time			
Path planning software focused on a different type of motion	difficulty of required motion to implement			
No standard form for integration process was planned	Lack of time			
Room allocations during workshops	unavailable space for work			
Permisssion difficulties to use engineering facilities	industrial projects are not priority at HWU			
Software installation issues	various versions			
Robot tansfer logistics	locations			

6 DISCUSSION

The observations made on the overall product design process are discussed in this section. To begin with, it was important to state the gaps between industrial and academic design projects. In industry the design process is most likely to be based on a previous design which is optimized based on former data and design plans that were generated over years of design experience. Moreover, companies have specialized design engineers in the field of the designed products, with many years of experience in design environment. Procedures are followed according to specific standards, which are written down in internal design manuals.

On the other hand, University design projects are usually done in theory without being practically applied due to cost and time limitations. Also students usually have no experience in the design process and follow educational design textbooks which tend to generalize procedures and include many assumptions because the goal is to familiarize the students with different design processes. One factor that the academic design project could benefit from, is the abundance of information and academic expertise that can be used to fill this gap between the two approaches that differ in complexity and applicability. One of the main reasons that this project was joint between two universities was the limited experience in robotic control software and lack of facilities needed to conduct the necessary research. This joint collaboration has its pros and cons which effected the overall robot design and development. One of the major benefits was the ability to merge the experiences needed to have a full team capable of proceeding with the design project.

Gantt chart shown in Figure 37, the light blue coloured bars represent planned durations for each phase, whereas the red bars represent actual time taken to complete the phases.

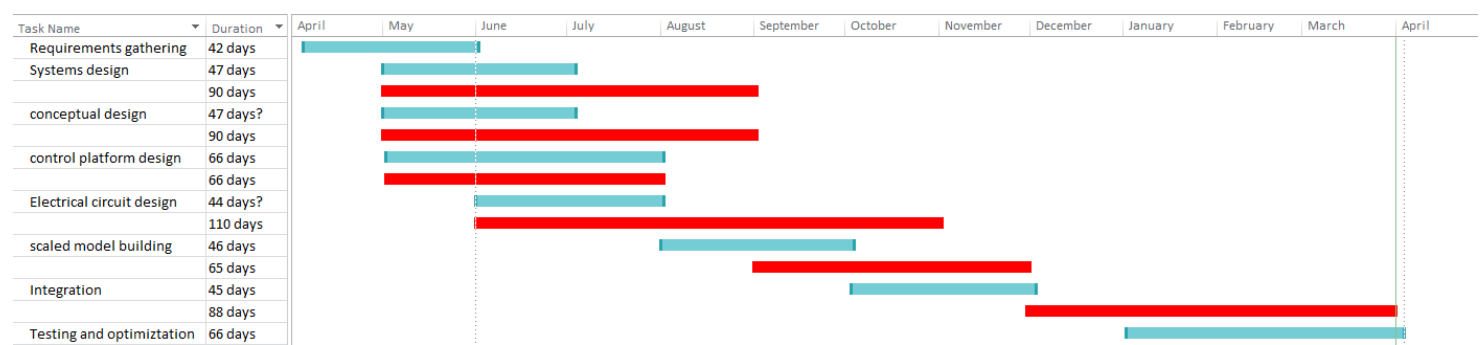


Figure 36 Gantt chart comparing planned and actual duration of each design phase

6.1.1 Integration Issues

The systems integration phase and electrical circuit design of the motor movements exceeded the planned durations by more than 50% of the allocated time frame. This excess time can be related to the approach the individual designers took for their designs. The integration method can be associated to the “big bang” integration testing. In the big bang process, all the software designs are integrated simultaneously increasing the chances of failures which will be difficult to find the causes. This time consuming process was demonstrated through the projects integration process where many issues were faced, such as the trajectory path plan problem which took more than two months to solve the problem, causing the bizarre path generations found in Figure 34. Another issue was the use of end-effector motors, which were not able to react to the loads generated by the applied pressure on the sweeping surface. This issue was considered to be a coding problem at first, which added to the wasted time on trying to find the solution in the wrong place. Such problems could have been avoided if the designers worked on a different integration approach such as continuous, in which isolated changes are immediately tested and reported when added to the overall code. Such approach will allow quick feedbacks to the designers where they can isolate any defects in the code and correct them as soon as possible. Another mistake done during the design process was the fact that designers worked in an environment, where only the best case scenario and outcomes occur exactly as they were taught throughout their study period. Unfortunately, in real life design this attitude is far from reality where engineers work on scenarios where they take into consideration the interfaces within their designs. Interface management is used to integrate smoothly the major barriers between different design disciplines that lead to a complex product [35]. Individual design decisions were made without considering the effects on other designers work. An example on interface issue is: when the motors were chosen, no consideration was made for the mechanical component weights. This was due to the lack of project overview and the students considered that their fellow colleagues already took such details into account.

6.1.2 Multidisciplinary Project

The project allowed students from different engineering disciplines to work together. This added to the complexity of the design process leading to miscommunication and difficulty in information handling between various designers. One very vital misconception adapted by the team members was the assumption that all members of the project had the same level of

knowledge in each subsystem design this created additional challenges on the team members were many design mistakes were made due to the lack of experience in a particular design difference that should have been addressed in a report or in one of the scheduled team workshops. The discussion during the workshops concentrated mostly on the results of each subsystem design without getting into the details of interfaces between all the designed systems. The lack of interface overview between the designed systems proved that there was an absence in coordination in the overall view of the project.

6.1.3 Process Control

The design process was managed through deadlines rather than being managed through bi-weekly milestones. This meant that problems were only raised after passing the deliverable deadline leading to extensions which effected the overall project progress. Many process control characteristics were identified during the design process;

Time delay is the most common issue that faces most project control process and all other characteristics can add to this delays. Disturbances such as the external issues faced along with design problems, multivariable interactions, and design constraints can be tackled in order to ensure a smooth process control. In this project the problems faced during the integration process shifted all the attention by focusing on finding solutions, this led to skipping the organization and following standards of industrial procedures that can help organize such a process.

7 CONCLUSION

The work done in this thesis identified the issues faced within the multidisciplinary design project of a train cab front cleaning robot. The method of observation helped find the gaps that caused delays, cost increase along with lower quality design outcomes by comparing project management data and formal reports. Although the issues had a negative impact on the final quality of the demonstration, the team managed to fix the issues within time and acceptable quality in order to demonstrate the scaled model in front of the industrial partners and RSSB. The observations conducted on the design process of the multidisciplinary project aimed to identify gaps in the methodology undertaken by engineering students that led to delays and system integration problems. Although sufficient testing and analysis of the robotic system was absent due to time limitations, initial tests proved that the project is feasible and the cleaning procedure practiced during the test met the requirements of the design.

There are many lessons to be learned from this project which will be applied in the near future for the development of the full scaled robot. The full scale design process will take into consideration all the issues faced during this project, as well as adapting engineering design tools such as interface issue management. Also documentation of the design in a way that allows the knowledge of one engineering discipline to be transferred to another using industry standards.

REFERENCES

- [1] M. Girod, A. C. Elliott, N. D. Burns, and I. C. Wright, "Decision making in conceptual engineering design: an empirical investigation," *Proc. Inst. Mech. Eng. PART B-JOURNAL Eng. Manuf.*, vol. 217, no. 9, pp. 1215–1228, 2003.
- [2] S. P. Tayal, "Engineering Design Process," *Int. J. Comput. Sci. Commun. Eng. IJCSCE Spec. issue "Recent Adv. Eng. Technol."*, pp. 1–5, 2013.
- [3] *The impact of academic research on industrial performance*. Washington, D.C: National academy of engineering, 2003.
- [4] W. David and S. David, "Autonomous Systems," *Johns hopkins APL Tech. Dig.*, vol. 26, pp. 368–376, 2005.
- [5] W. Chris and S. Gould, "Here's when robots will start beating humans at every task," *Business Insider UK*, 2017.
- [6] H. David and P. Kinsella, "The Transition From Steam." [Online]. Available: <http://www.davidheyscollection.com/page30.htm>.
- [7] "History Tuesday: The Car Wash," 2013. [Online]. Available: <http://www.davison.com/blog/2013/04/23/history-tuesday-the-car-wash/>.
- [8] "50 years of car washes," 2012. [Online]. Available: <https://www.washtec.com.au/deals/pages/Happy-Anniversary.html>.
- [9] "ISTOBAL." [Online]. Available: <http://www.istobal.com/uk/>. [Accessed: 07-Jun-2017].
- [10] Christ wash systems, "Train wash C7000." [Online]. Available: <https://www.christ-ag.com/cms/produkte/zug-strassenbahnwaschanlagen/train-wash-c7000-soa/?L=8>.
- [11] B. Siciliano and O. Khatib, *Handbook of Robotics*. Springer, 2008.
- [12] H. Jurgen, G. D. Tipaldi, and W. Burgard, "Null space optimization for effective coverage of 3d surfaces using redundant manipulators," *Intell. Robot. Syst. 2912 IEEE/RSJ Int. Conf.*, pp. 1923–1928, 2012.
- [13] A. Safari, "Conceptual Process for Designing High-Technology Products: Case Study of a Litter- Collecting Robot," in *Robotics, Automation, and Control in Industrial and Service*

- Settings*, Z. Luo, Ed. United States of America: Engineering Science Reference, 2015.
- [14] T. E. Jenson and M. . Andreasen, "Design Methods in Practice - Beyond the 'Systemic Approach' of Pahl & Beitz," *Design*, pp. 21–28, 2010.
- [15] G. Pahl, W. Beitz, J. Feldhusen, and K. Grote, *Engineering Design*, Third Edit. London: Springer, 2007.
- [16] T. Tomiyama, P. Gu, Y. Jin, D. Lutters, C. Kind, and F. Kimura, "Design methodologies: Industrial and educational applications," *ELSEVIER*, pp. 543–565, 2009.
- [17] Researchgate, "Design process example of a gripper robot." [Online]. Available: https://www.researchgate.net/figure/289726879_fig1_Figure-4-Flowchart-for-the-development-of-gripper-robot. [Accessed: 05-Jun-2017].
- [18] "International Council on Systems Engineering," 2004. [Online]. Available: <http://www.incose.org/Home>.
- [19] ICOSE, *Systems Engineering Handbook*, Fourth Edi. San Diego: John Wiley & Sons, 2015.
- [20] T. Pyzdek and P. Keller, *The Six Sigma handbook*. 2010.
- [21] R. J. Mutchnik and B. I. Berg, *Research methods for the social sciences- practice and applications*. Boston, Massachusetts: Allyn and Bacon, 1995.
- [22] A. Krslin, "Systems design of a robotic train cab front cleaner," Cranfield University, 2016.
- [23] L. Rubio Garcia, "Conceptual design of cab front robotic cleaner," Cranfield University, 2016.
- [24] W. McColl, "Cab front cleaning robot: control implementation and prototype construction," Heriot-Watt University, 2017.
- [25] C. Mann, "Cab Front Cleaning Robot – Modelling, Implementation, and Vision based Wiper Detection," Heriot-Watt University, 2016.
- [26] J. Moura, "Application of force control to a robotic manipulator for sweeping a non-flat surface," Heriot-Watt University, 2016.

- [27] Office of Rail and Road, "Passenger Rail Usage 2016-17 Q3 Statistical Release," 2017.
- [28] C. Chaplain and E. Standard, "A high-speed London to Frankfurt train will launch as early as 2020," *Business Insider UK*, 2017.
- [29] D. Burt, S. Petcavage, and R. Pinkerton, *Proactive Purchasing in the Supply Chain: The Key to World Class Procurement*. United States of America: The McGraw Hill Companies, 2012.
- [30] T. Tomiyama, M. S. Erden, G. Corfield, S. Jarret, and R. Walker, "RRUKA Feasibility Study Proposal Competition: 'Application of Robotics and Autonomous Systems to Rolling Stock Maintenance,'" London, 2015.
- [31] M. S. Erdin and M. Joao, "Control and path planning approach for a cab front cleaning robot," *5th Int. Conf. trough-life Eng. Serv.*, 2016.
- [32] "HepcoMotion." [Online]. Available: <https://www.hepcotion.com/>. [Accessed: 09-Sep-2016].
- [33] "Igus gantry." [Online]. Available: <http://www.igus.co.uk/>. [Accessed: 04-Sep-2016].
- [34] J. Gere, *Mechanics of Materials*, Sixth edit. Belmont: Thomson, 2004.
- [35] A. Vandeveld and R. Van Dierdonck, "Managing the design-manufacturing interface," *Int. J. Oper. Prod. Manag.*, vol. 23, no. 11, pp. 1326–1348, 2003.

APPENDICES

Appendix A Depot Visits

A.1 Remarks from Depot Visits

Remarks:

*1	Integration of fully developed industrial robots (exp. SCARA, KUKA) is not desirable
*2	Efficient use of water, cleaning chemicals and power
*3	Extensive everyday use [4]
*4	[6] Considering current Side Cleaning mechanism activation switches
*5	[7] Considering the fact this system is being developed for future depot designs there is a need to incorporate possibility of simple way to improve the system
*6	Special attention in terms of cleaning quality applies to windscreen and lights according to Bombardier (Drivers can reject cleaning results if they find windscreen not suitable for safe train operating)
*7	Need for quality control in case of cleaning system failure or fault cleaning process. Also can be self-learning information loop.
*8	To apply sufficient rubbing force for purpose of cleaning and to not apply too much force resulting in damaging either train or robot
*9	Recognition of an object (train) in estimated cleaning space and ability to approach and touch train surface with minimum tolerance (for end effector to perform cleaning action)
*10	Pressure angle is an angle between the vector of cleaning force and normal of the surface. For optimised cleaning pressure angle should be optimised at every point on train.
*11	Bombardier [4] suggested adjustable cleaning program differentiating in quick or a trouble wash
*12	Current manual cleaning procedures all follow logical approach of cleaning taking start at the top then continuing to bottom of the train front
*13	Current logistics of train movement and more importantly water, cleaning chemicals, power supply and drainage availability drive depot s operator to consider this as a best option
*14	To avoid loss of time and inconvenience of train stopping as well to better integrate the new system with existing side cleaning system which requires train to move through with speed of 3mph
*15	[6] Current cleaning facilities layout demand trains passing through even for non-cleaning purpose
*16	Not damaging parts due to pressure, chemicals or water. Special care to be considered for lamps and windscreen.
*17	[5] [6] Current manual cleaning uses brushes to apply cleaning force that effectively cleans, which is a very small surface coverage and concludes in many repetitive moves to cover whole cab front.
*18	Train operators conduct train preparation before voyage and their key aspect of cleaning performance is spotless of the windscreen. Due to material -glass, there is no less restriction of cleaning force.
*19	Automatization of the cleaning process aims at removing manual labour due to safety reasons but also should improve cleaning/maintenance time since train is only serving its purpose as it is in use
*20	Due to the train design Front cab is faced into opposite direction than the Rear cab. Additionally considering current depot logistics trains should be able to enter the system from any direction to keep the optimised level of the depot procedures.
*21	Currently side cleaning is not performed in sub-zero temperatures due to nozzle and flaps freezing. However front end consists of windscreen cleaning which should always be performed due to safety reasons

Information**Resources:**

- [1] RRUKA Feasibility study proposal V4 (presented and approved when project was chosen to be sponsored; before May 2016)
- [2] RSSB meeting minutes (Paras) and personal notes (Andraž) (discussed in meeting in London 13.5. 2016)
- [3] Lunch with Rail officials; Tomiyama email (email content 19.5.2016)
- [4] Depot visits report (Luis Rubio Garcia)
- [5] Current Depot Train Cleaning Function Modelling (Andraž Kršlin)
- [6] Current cleaning procedure Photo material (Andraž Kršlin)
- [7] Capt. Dean Leroy Schneider (1993) Reliability and maintainability of modular Robot Systems: A Roadmap For Design

A.2 List of Requirements

KVA	Cost [1]	Source	Reliability	Source	Autonomous control [1]	Source	Depot integration	Source	Cleaning efficiency	Source
SVA	Uncomplicated arm design	*1	Robust system	[1] *3 [4]	Automatic Surface detection	[1] *9	Use of existing power and water supply	[1] [4]	Avoiding obstructions like wipers	[2]
	Material		Cleaning chemical corrosion resistance	[2]	Automatic pressure detection	[1] *8	Use of drainage systems	[1] [4]	Careful lamp cleaning	[2]
	Efficient use of inputs	*2	Easy to maintain		Pressure angle adjustability	[1] *10	Integration with current automated side cleaning system	[4] *13	Effective removal of bugs and other biological material	[3] [4]
			Waterproof		Adjusting to tolerance of train stopping position	[1]	Cleaning a moving train	[2] [4] *14	Minimum damage to the train	*16
			Reliable activation and deactivation	*4	Generation of optimised cleaning path	[4] [5] *12	Enable passage of trains when not active	[4] *15	Effective removal of dust, mud, diesel fume, oil stains	
			Subsystem modularity	*5	Recognition of lights and windscreen	[4] *6 *18	Avoid overheads	[4] [6]	Reach pockets and concave areas	[1]
					Feedback on work quality	*7 [4]	Bi directional cleaning	*20	Cleaning of between carriage space	[2], [4]
					Multiple cleaning programs	[4] *11			Surface coverage of cleaning	*17
									Cleaning chemical supply	[4] [5]
									Water supply	[4] [5]
									Efficient cleaning of windscreen	[4] [5] *18
									Cleaning at sub-zero temperatures	*21
									Match manual cleaning performance	*19

Figure 37 Krslin KVA and SVA table [22].

Appendix B Weight Estimation

Table 10 Robot weight estimation

Item	quantity	length	unit Mass	total M
		mm	kg	
Vertical Gantry	2	3870	23.35	46.7
V gantry motor	1			0
V gantry carriage	2			
Horizontal Gantry	1	3120	19.6	19.6
H gantry motor	1			0
H gantry carriage	2			0
EF Gantry	1	1720	12.6	12.6
EF Gantry motor	1		3.6	3.6
EF motor	3		0.126	0.378
Brush	1		2	2
Force Sensor	1		0.15	0.15
Water pipe	1	1720		0
Chemical Pipe	1	1720		0
			Total:	85.028

Appendix C Prototype assembly

This appendix provides pictures of the prototype assembly and train front cab modelling.

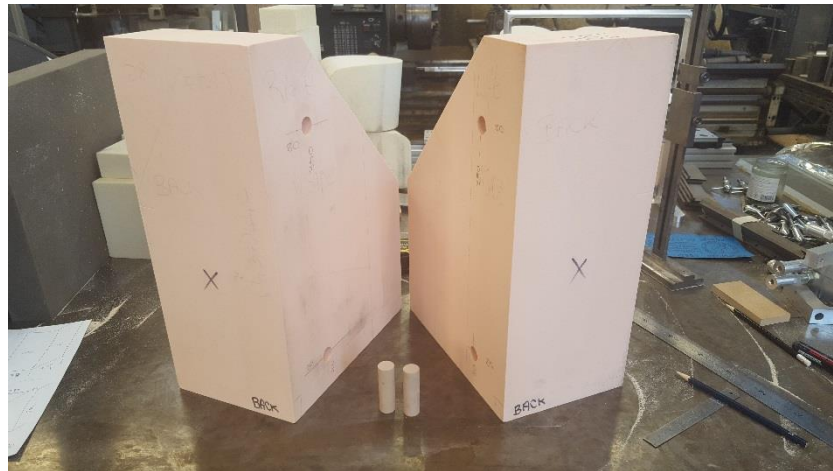


Figure 38 Front CAB model

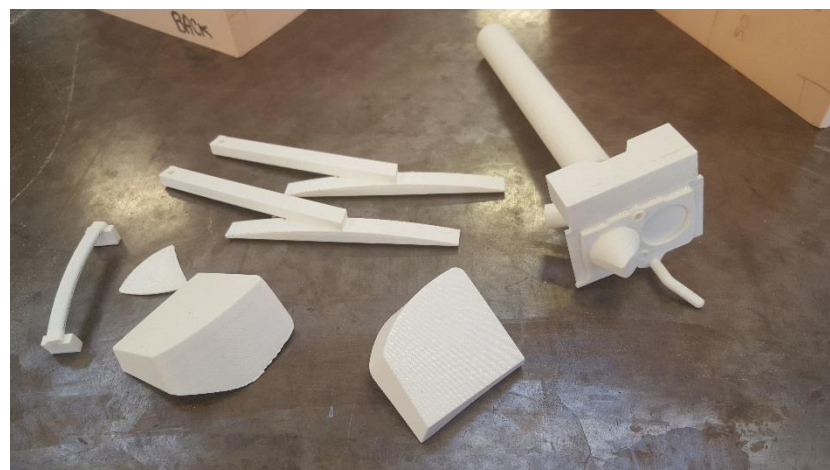


Figure 39 3D printed components



Figure 40 Horizontal Gantry motor attachment

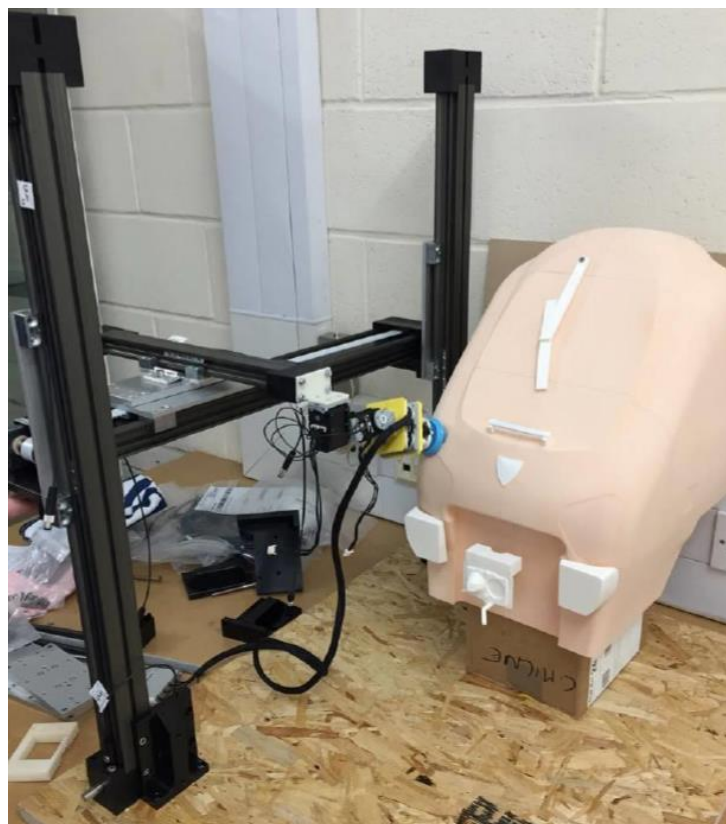


Figure 41 Gantry assembly at Heriot-Watt University

Appendix D Finite Element Bending Moment Results

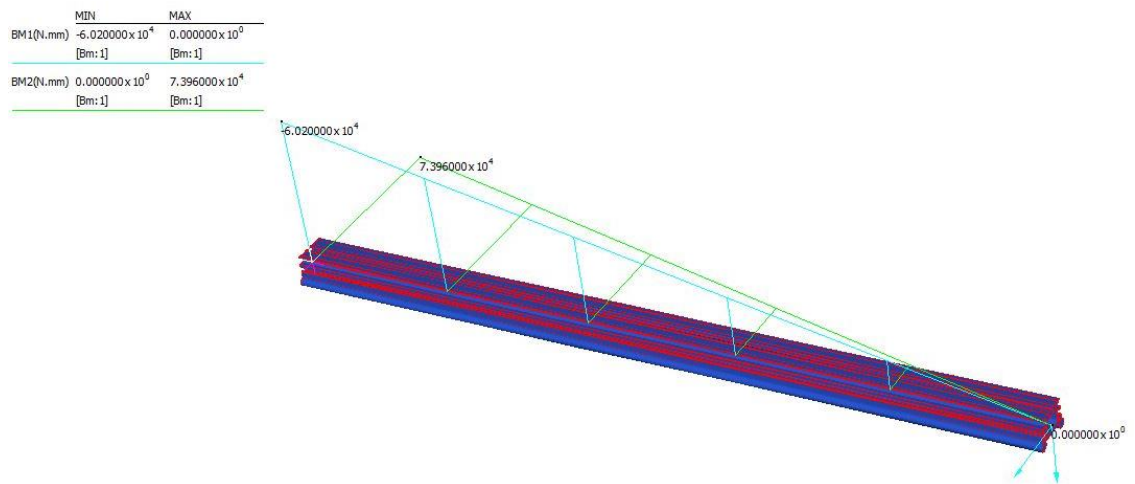


Figure 42 Bending moments acting on end-effector gantry.

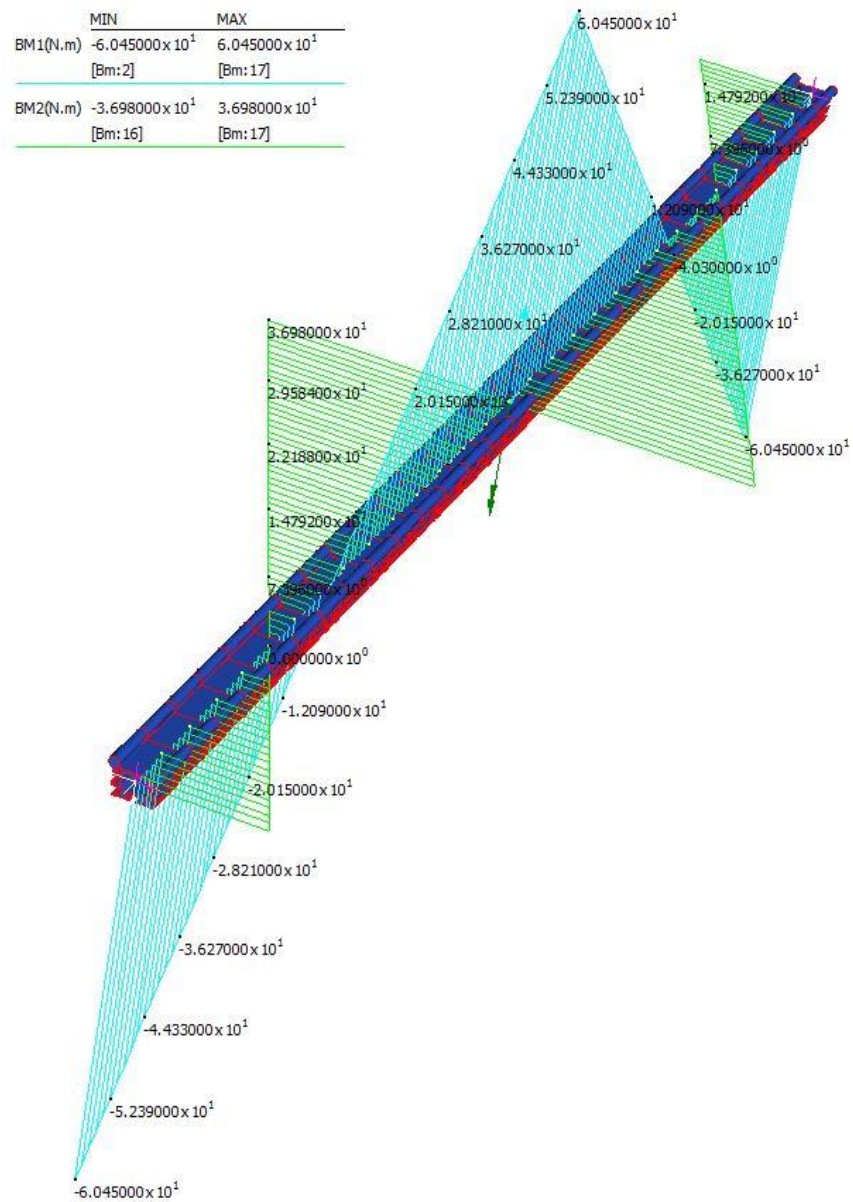


Figure 43 bending moment acting on horizontal gantry.

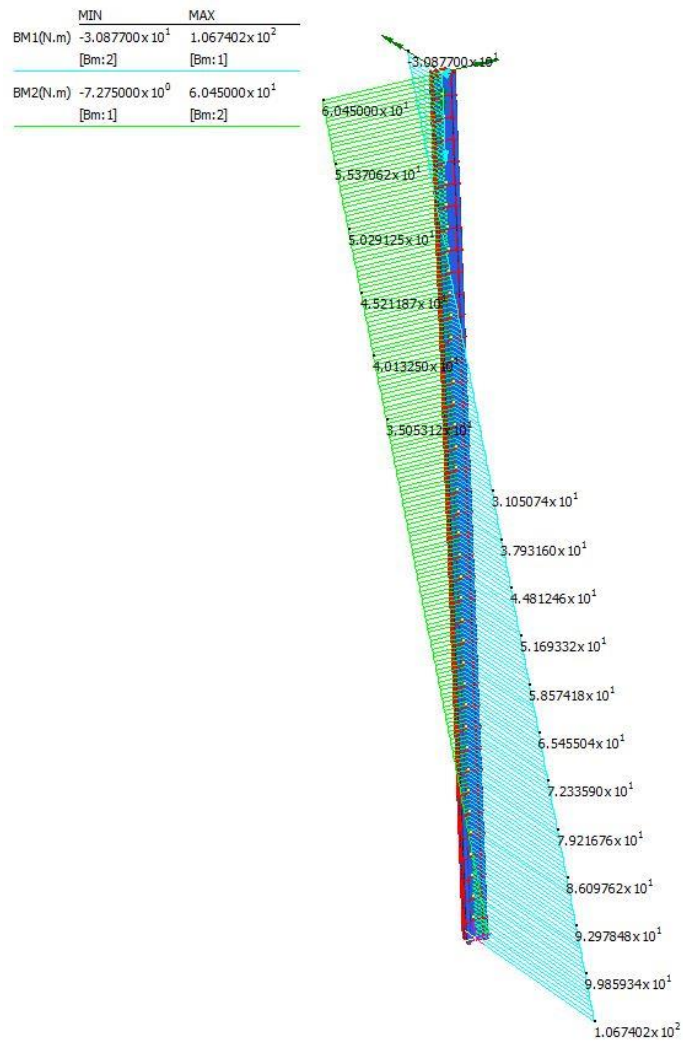


Figure 44 Bending moment acting on vertical gantry.

Appendix E Monthly Progress Report to RSSB Template



Project update

Project Title: Robotics RAS3 'Cab front cleaning robot/

Topic: Robotics

Completed by: Gerard Taykaldiranian

Project reporting period

Start date: 03 March 2017

End date: 31 March 2017

Deliverables		
Description	Work completed (%)	Due date (actual)*
D1: Document of description of the entire system concept	100	01 Jul 2016
D2: Initial Mechanical Design in SolidWorks/CAD	100	01 Aug 2016
D3: Optimized Robot arm Design	100	08 Sep 2016
D4: Rotating-brushes physically implemented	80	27 Oct 2016
D5: Software implementation of force control	95	25 Nov 2016
D6: Software implementation of path planning	90	26 Dec 2016
D7: Working 1/8 th scale demonstrator	95	04 Apr 2017

**These dates should reflect those from the original plan*

Key achievements
<ul style="list-style-type: none">• The end effector is reacting to the surface using the force control• The robot is shipped back to Cranfield where final assembly and tests will be carried prior to the demonstration date• Raster scan motion implemented on the front cab train model

Deliverables

- *NO deliverables at this point*

Delays, challenges and risk

- *The vision sensing was tested separately, the aim at this point is to stop the end effector from rotation when wipers are detected.*

Implementation/collaboration opportunities

- *NO new implementations at this point*

Change recommendations

- *No Change recommendations*

Assistance or requirements

No assistance required as yet.

Planned activity coming up

- *Assembling the Robot in Cranfield.*
- *Coating the surface of the 1/8th scale model front train cab to minimize friction*
- *Heriot-Watt team will join for 3 days to finalize and make sure everything is running smoothly for the demonstration.*



Include updated Gantt chart below

Gantt chart will be provided after the visit to Heriot-Watt University

Appendix F Baxter robot



Figure 45 Baxter robot used to test force sensor control [26]

Appendix H Publications



Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 59 (2017) 61 – 66



www.elsevier.com/locate/procedia

The 5th International Conference on Through-life Engineering Services (TESConf 2016)

Systems and conceptual design of a train cab front cleaning robot

Tetsuo Tomiyama^{a,*}, Luis Rubio Garcia^a, Andraž Kršlin^a, Gerard Taykaldiranian^a

^a Cranfield University, Building 50, Manufacturing Department, Cranfield MK46 0AL, United Kingdom

* Tetsuo Tomiyama. Tel.: +44 (0) 1234 750111. E-mail address: t.tomiyama@cranfield.ac.uk

Abstract

This paper presents and briefly describes the methodology used to get the systems and conceptual design of a train cab front cleaning robot. While the sides of the trains are cleaned by a mechanised washer, the cab fronts are cleaned manually which imply a number of health and safety issues. The aim of this project is first to carry out an analysis of the current procedures in order to detect the possible gaps in the process, generating a list of requirements that will make possible the conceptual design of a cleaning system that fulfil those requirements. The proposed solution includes the division of the system in various subsystems where different solutions for each subsystem will be considered, analysed and selected as a final option to develop a prototype. This paper focuses in the main structure of the robot that holds the end-effector, different conceptual designs are shown that comply with the requirements set in the systems design.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of the The 5th International Conference on Through-life Engineering Services (TESConf 2016)

Keywords: Cleaning robot, systems design, conceptual design, product development

1. Introduction

Train exterior cleaning is usually conducted by a mechanised washer. However, this washer cleans only the sides of the body. It does not clean the cab front nose or the body-end panels between carriages. The train cab front nose often consists of complicated shapes and the body-end panels between carriages sometimes are not cleaned at all. This leads to a huge amount of manual labour work for exterior body washing, creating a number of health and safety issues including working under 25kV overhead wires, working around electrified third rails, and working at heights, especially problematic during the night and in bad weather conditions (See Figure 1).

Cab front cleaning is carried out in a very similar way at every depot in the UK. However, it lacks of any standard procedure, efficiency and post-process inspection. Sometimes the timings available for this task are very short and each time the process is slightly different. The pressure applied when scrubbing the train surface is varied, the time spent cleaning different areas of the front cab nose is relatively random and

even the quantity of detergent and water applied is not constant every time.



Figure 1: Member of the depot staff performing the cleaning procedure of the train cab front.

For the reasons pointed out above, Cranfield University in collaboration with Heriot-Watt University proposed a