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

Systems and conceptual design of a train cab front cleaning robot

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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.

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

feasibility study of a cab front cleaning robot. This paper presents the systems and mechanical design aspects of that study. This idea screening stage, according to the New Product Development process [1], have focused on data gathering by visiting different depots, analysing the current processes in order to identify gaps and develop the systems design following set based concurrent engineering practice [2]. That results in obtaining the design requirements and creation of the functional diagram in order to establish the specifications necessary for the conceptual design. Once the specifications were pointed out the system was divided in different subsystems of which the main one was the end-effector of the robotic arm cleaner. Different solutions were evaluated resulting a number of candidates for the prototype in the next phase of the project.

2. Aim and Objectives

2.1. Aim

The aim of this project is to develop a proof-of-concept prototype of a semi-autonomous robotic cleaner for train nose-head as well as body-end panels. This stage of the project focused on performing a concurrent innovative design to address the mechanical structure and end-effector.

Besides detecting the specific requirements by the methods that will be explained later in this paper, the system should be also cost effective, robust, retrofitable and easy to operate.

In terms of the scientific approach the procedures presented in this paper must answer two different questions. First is how many devices or arms the system needs. Secondly what is the best arm mechanism to provide basis for the end-effector design?

2.2. Objectives

The main goals of the entire project are:
- To design the entire system considering the current infrastructure at the depot.
- To design the robot arm including kinematics analysis, dynamics analysis, and optimisation of the arm design considering the control aspects.
- To design the cleaning device (end-effector) including chemicals and water supply, brush moving mechanisms and contact detection mechanisms.
- To design the robot arm control system for surface detection and surface coverage for the cleaning purpose of train cab front nose and in-between the carriages.
- To build a 1/10 scale demonstrator to prove the feasibility of the concept.

While the main objectives of the procedures presented in this paper are:
- To present a detailed report of the actual situation of the cab front cleaning procedures pointing out the gaps and possible areas of improvement.
- To establish list of requirements and design parameters using set based concurrent engineering approach [2]
- To present the conceptual design of the cleaning device that fulfil the specifications and will be the starting point

for the basic engineering or Front-End Engineering Design (FEED) stage.

3. Methodology

This project aims to resolve feasibility issue of incorporating and designing an autonomous robot for train cleaning. That is essentially a project of a new product development. Any products in the market try to solve problems that its buyer would potentially seek to solve. The same was in this case and following the guidance of Goffin [3] the first part of the methodology bellow was created. First step, the data acquisition, is the most important, since if the problems of the customer are not effectively collected or are miscommunicated, then it is likely that the end product will fail to deliver the desired performance. The next step is data processing in which the information gathered is organised and translated to an engineering language. That allows to see the project in an objective and quantifiable (as much as possible) perspective. This serves as a foundation for a successful solution development at the last stage of the methodology. In this stage ideas are created and tested, the best ones are developed into concepts and in the end the one with the best design is selected to be prototyped.
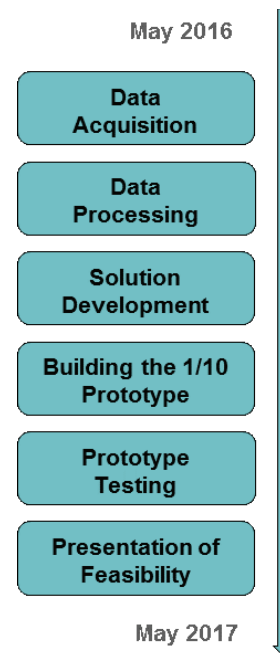
Figure 2: Overall project methodology.

Although the whole project consists of also prototype building and testing that is out of the scope of this paper.

4. Current Cleaning Procedure

4.1. Data Acquisition

To achieve best solutions in the design phase it is critical that right customer needs are addressed. To obtain best possible information on the current cleaning procedure three different depots were visited. The team visited Chiltern Railways diesel train depot in Wembley, London Overground depot for electric trains in Willesden Junction and Bombardier diesel train depot in Central Rivers.

For each visit a list of questions and a checklist of desired documents were prepared and communicated with the hosts. Photos and videos, 3D scans using the Google Tango device were also obtained. That was an important part of data acquisition, since 3D models of the cleaning area and the train itself are much more helpful than blunt photos. The use of the 3D model also allowed the team to obtain measurements of certain details that are not accessible at the site. That information supported by the videos of the cleaning procedures and insights from employees directly connected to the cleaning processes helped the team to create an overall image of the current state of affairs.
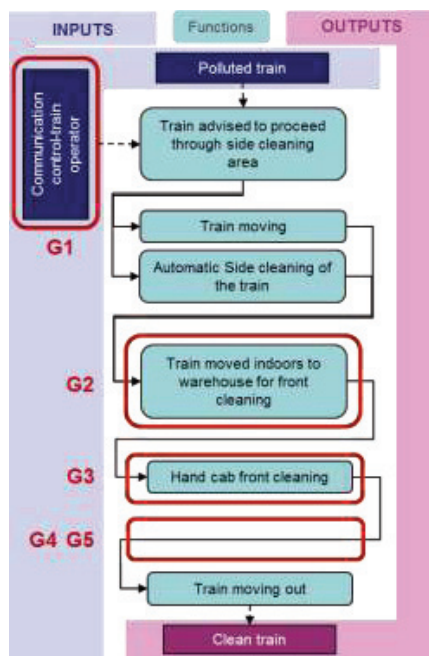

Figure 3: Functional diagram of the generalised common cleaning procedure.

As seen in Figure 3, the current cleaning procedure consists of a few steps. Cleaning the whole train is part of the maintenance plan that many depots combine into one continuous operation. However, front cab cleaning is performed separately. The main reason is that train has to be brought to a maintenance shed where a trench and other infrastructure provides maintenance work with a relatively convenient space for cleaning. Some depots perform cab front cleaning at fuelling stations where apart from cleaning, the

trains are supplied with fuel and fresh water and wastewater is drained. This process is either performed before or after side cleaning of the train which uses designated automated machines located elsewhere in the depot.

Whatever the logistical sequence of side and front cleaning is, the cab front cleaning is still a heavy manual job. Due to that nature it poses health and safety risks to cleaners. The most obvious and serious is the risk of electrocution if water comes to contact with overhead lines or a third rail which carry high voltages. Therefore, the use of normal household pressure water hoses is banned meaning a great consequence on the cleaning performance. Also as shown in Figure 1, cleaners have to perform the work walking around the maintenance trench on wet slippery concrete which poses a great risk of falling into the trench. Additionally, the cleaner stands on the ground and has to clean the top of the cab front using a brush mounted on a long handle, which results in an awkward body postures as well as poor cleaning performance in that area compared to the middle and lower section of the cab front. This poses a problem, as the most important cleaning target is the windscreen which is usually located on the upper half of the train. All of these issues and risks lead to a conclusion that automated cleaning would increase cleaning performance as well as remove a serious health and safety risks for the depot employees. Besides, human resources would be freed from an intensive and repetitive task and could spend time on more important maintenance jobs.

Considering all said above main gaps in the process were identified. They will serve as a centre point of attention for the design solutions later in the project.

Table 1. Gap of the current cleaning procedure as found in Figure 3.

Gap no.	Identification	Possible benefits
1	Possibility of automatic detection of train by RFID	Support to control room.
		Input information for cleaning mechanism
2	Unnecessary logistics moving the train	Fit the new front cleaning system with existing side cleaning
3	Manual front cleaning	Remove the cleaners from risky working environment.
		Improve the cleaning results by better cleaning devices
4	No cleaning of gaps between carriages	Design the new system including this feature
5	No cleaning result inspection	By automating the process, the results would become standard and controllable

5. General Requirements

As explained above one of the crucial points of the product development is transformation of intangible customer needs into clear requirements. Following the logic of Set-Based Concurrent Engineering [2] principles requirements were first divided into main groups called Key Value Attributes (KVA) pointing out a group of requirements targeting specific aim.

These main groups then consist of Secondary Value Attributes (SVA) which are essentially more detailed requirements of the same topic. That allows the systems engineer to better identify the most crucial requirements to be met.

As we can see in the Table 2 there are five KVA in this project current front cab cleaning operation does not involve many human resources. Considering that the new system should not be a big investment for the maintenance companies, Cost is the first KVA. Connected to Cost, Reliability (or Robustness) was set as the second KVA. A reason for it is that the new system has to perform various repetitive movements as well as supplying water and cleaning chemicals efficiently in all weather conditions and as continuous as possible to achieve high productivity. Introducing a new product always poses a question of how it will perform under real environment conditions. The third KVA is the Depot integration which aims at the successful fitting of the new machine into current layouts as well the procedures as efficiently as possible. In the end, it comes to the core function of the system; the cleaning itself. The fourth KVA is the Cleaning efficiency which is grouping all requirements that need to be met in order for cleaning result to meet the required standards. Because the system is planned to be autonomous, the autonomous control is the last KVA. All aspects that need to be met in the group of cleaning efficiency request a new system to perform autonomously with no human interaction.

Table 2. List of requirements.

KVA				
Cost	Reliability	Autonomous control	Depot integration	Cleaning efficiency
SVA				
Uncomplicated arm design	Robust system	Automatic Surface detection	Use of existing power and water supply	Avoiding obstructions like wipers
Material	Cleaning chemical corrosion resistance	Automatic pressure detection	Use of drainage systems	Careful lamp cleaning
Efficient use of inputs	Easy to maintain	Pressure angle adjustability	Integration with current automated side cleaning system	Effective removal of bugs and other biological material
	Waterproof	Adjusting to tolerance of train stopping position	Cleaning a moving train	Minimum damage to the train
	Reliable activation and deactivation	Generation of optimised cleaning path	Enable passage of trains when not active	Effective removal of dust, mud, diesel fume, oil stains
	Subsystem modularity	Recognition of lights and windscreen	Avoid overheads	Reach pockets and concave areas
		Feedback on work quality		Cleaning of between carriage space
		Multiple cleaning programs		Surface coverage of cleaning
				Cleaning chemical supply
				Water supply
				Efficient cleaning of windscreen
				Match manual cleaning performance

6. Conceptual Design

The system has been divided in four subsystems:

- Control system.
- Base.
- Arm/structure.
- End-effector.

The control system is being developed by our colleagues at Heriot-Watt University [4]. The base, arm/structure and end-effector are passing the conceptual design process. This paper will show the arm conceptual design.

6.1. Arm/structure Conceptual Design

The first step in a robot arm/structure design is to define the work area of the system. For that purpose, the team used CAD data of the Bombardier Class 22x train as an example cab front that the system will be able to clean. As shown in the Figure 4 the total workspace that the system will cover is a volume of 2800 mm wide by 3100 mm tall by 3000 mm deep. Additionally, the approximate space the system will have to cover will be 10.5 m² as can be observed.
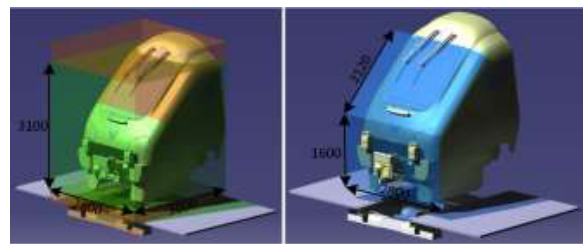

Figure 4: CAD image to define the work area and the cleaning area of the robot

The front area is barely possible to cover with only one device, especially if the cleaning system is positioned in the side, which was one of the restrictions analysed in the problem definition.

This means that either the work area of the system has to be split. The shape of the train is symmetrical so the first assumption is to divide it by the vertical symmetry axis.

With the general requirements and the work area defined multiple concepts where generated. A total of eight concepts fulfilled the requirements and were evaluated.

The Table 3 shows the results of the evaluation of the eight designs pointing out that there were two design that fulfil the requirements better than the rest. Since their score was almost the same it was decided to further investigate both solutions.

Table 3. Concept evaluation table.

End-effector type	Concept Name	Concept Code	Evaluation Mark	Evaluation in %
Belt	Belt cleaning 1	**A1**	29	0,48
	Belt cleaning 2	**A2**	39	0,65
Rotating circular brush	Full Arm	**A3**	46	0,77
	Door concept 1	**A4**	46	0,77
	Foldable door	**A5**	43	0,72
	Swing doors	**A6**	53	0,88
	Open Arm	**A7**	52	0,87
Rotating Cylindrical roll	Cylindrical roll	**A8**	40	0,67
	Achievable max score		60	1,00

6.2. Concepts selected

6.2.1. Swing Doors Structure Concept

The system consists of two identical frames (grey) on each side of the train tracks. Each frame has a swing door (yellow) to which an end effector (red) is attached. Swing door can move along the z and y axes while the end effector within the swing door frame can move along the x axis. With additional rotations of swing door end effector is able to reach all surface points of the cab front as well gap between carriages. The system has six degrees of freedom (DOFs).
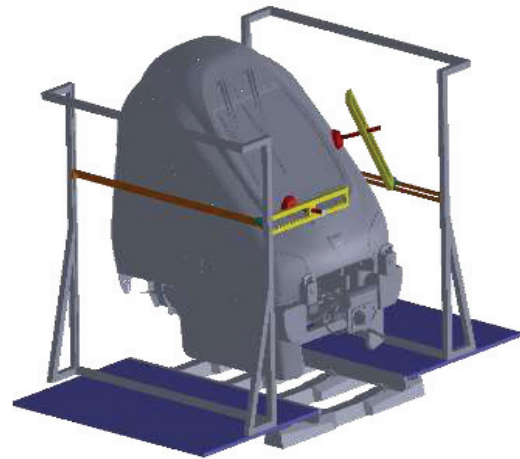

Figure 5: Swing doors structure conceptual design

6.2.2. Poll Articulated Robotic Arm

The system consists of a poll to which one or more robotic arms are attached. Two pillars are positioned (Blue) on each side of the train. The shoulder (Light blue) can move along the poll in the z axis and rotate around the same axis allowing the arm to open like a door. The upper arm (Green) can rotate to adjust the position of the elbow of the arm. The forearm (Yellow) can rotate with respect to the elbow to position of the wrist. The wrist (Orange) can rotate around the axis of the forearm to adjust the end-effector. The end effector can also rotate itself to adapt to the surface or clean the gap between carriages. The robot is a 6 degree of freedom robot. It has 5 revolute serial joints and one linear joint located at the shoulder that allows the movement along the poll.
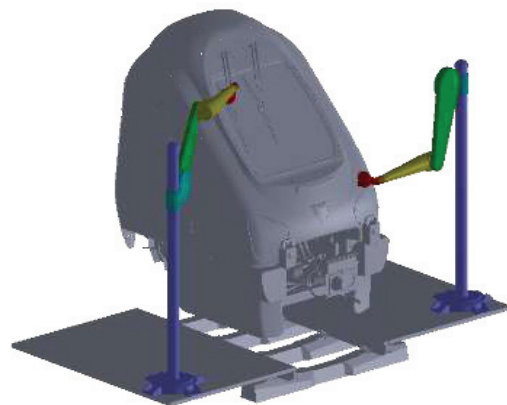

Figure 6: Poll articulated robotic arm conceptual design

7. Conclusions

Extensive analysis of the current manual front end cleaning has pointed out areas that can be improved resulting in a better cleaning performance as well as the release of cleaning staff from potentially health and safety unfriendly work environment. These areas serve as a starting point for the system development and also present the key deliverables of the new system. Subsequently system requirements were drafted and system structure was established.

In this paper the main focus was on the design of the robot arm which carries the end effector which actually performs the cleaning itself. The arm design is crucial since it dictates the limitation and possibilities of the new cleaning procedure and integration into current depots; physically and operationally.

The design phase delivered two possible designs. Although they look at the first sight very different from each another they are both able to well-perform required tasks of the subsystem. The complexity does not differentiate either; both are 6 degrees of freedom systems. Similarity is only seen in the design choice of two arms, one per train side. That relieves the arm design of stresses and increases the cleaning performance.

The process now moves to the conceptual design of the base and end-effector and the final concept will be decided taking into account the control system as well. Furthermore analysis of the depot integration will be performed along with analysis of the cleaning sequence. All that should provide additional requirements which will help to choose the optimum arm design.

Once the final solution is chosen the conceptual design phase ends and the basic engineering or Front-End Engineering Design (FEED) stage will start where the concept will be optimised in order to build the prototype.

Acknowledgements

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