Design, construction and operation of a REPOINT laboratory demonstrator

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ABSTRACT

The REPOINT project, led by Loughborough University, has been active since March 2011. It seeks to improve the reliability, safety and maintainability of track switching technology, with the aim of increasing network capacity and lowering operating costs. To do this, the project is exploring combining mature concepts from other industries such as fault tolerance, line-replaceable units and passively safe design, with novel mechanical arrangements, in order to bring about a step change in performance. One design, based around a stub-switch arrangement, has showed particular promise and is the currently the subject of three patent applications covering the novel mode of operation. A laboratory-scale demonstrator of all key subsystems is currently under construction, under funding from the FutureRailway.org team. This is integrated with test and monitoring equipment, alongside a rapid-prototyping control system. This first-generation design will be used to prove the concept of operation and to develop the associated control and monitoring technology.

The goal of this paper is to provide an overview of the REPOINT project to date, and the design and operation of the proposed novel REPOINT design. This paper firstly introduces the REPOINT project and highlights of the proposed novel design. It then discusses the simulation, modelling and design of the demonstrator rig, and the associated test and development equipment. The conclusions highlight the progress so far – on the REPOINT project and the Demonstrator rig - and comment upon potential next steps towards network deployment.

1 INTRODUCTION

Railway track switching provides necessary flexibility to a rail network, allowing vehicles to take a multitude of routes. However, track switches represent single points of failure, and even when operational can introduce capacity constraints due to the design of physical track components and the associated signalling systems for control and operation. Switches are expensive and complex designs when compared to equivalent plain line (1, 2). Their population is therefore generally optimised at design time - alongside a known timetable - in order to minimise initial outlay and substantial ongoing maintenance costs. This can compound the negative effects upon network delay performance during timetable perturbation. With the anticipated move towards cab-signalling, the only remaining ‘active’ line-side assets will be switches and level crossings, and these will thus contribute an ever increasing portion of network delay totals without significant further work to improve performance.

In the United Kingdom, open-access statistics (3) show passenger counts are at their highest level since re-privatisation, with some lines now running at or near operational vehicular capacity. This fact, when coupled with cross-industry initiatives such as the `24/7 Railway' (4), `On-time Railway', and increasing overnight freight utilisation as suggested in the recent IMechE ‘Rail Freight Report' (5), is much reducing the portion of time available to take maintenance possessions of infrastructure. Importantly, it is often not the physical maintenance act itself which is expensive in monetary terms, but instead the time the asset is out of use - whether this be for a planned maintenance intervention or unanticipated failure. This monetary cost is therefore associated to a capacity cost.

It is commonplace in some industries to replicate critical components in order to increase whole-system reliability and/or as a step to enable improved maintainability (6). Commercial aircraft, for instance, would typically have triplex or quadruplex redundancy built in to flight control systems as repair or replacement - due to an incipient fault in a single subsystem - must necessarily wait until after the aircraft has landed. This approach has made some inroads into certain rail industry assets – signalling bulbs and SSI (Solid State Interlocking) being prime examples. Indeed, SSI was state of the art in safety critical computing when under development in the 1970’s, and other industries adopted the principles therein soon afterwards (7). However, multi-channel redundancy and/or extensive fault tolerance have not yet been adopted for track switches.

Recognising the restrictions switches place upon network performance, and the opportunities to exploit technologies, techniques and approaches from other industries, the REPOINT project was initiated in 2011. The goal was to investigate what could be changed in existing switch designs, and to propose novel concepts, in both physical design and operating rules. The project was also to quantify what effect these changes would have. The project background is covered in more detail in section two. As part of the investigation, a novel design of track switch was devised, which is introduced in section three. This paper covers the modelling, simulation, and construction for a 384mm gauge laboratory demonstrator of this novel arrangement. This work is presented in sections four and five. The demonstrator is now complete and operational, and the next steps in the research and development work are discussed in section six.

2 BACKGROUND

The REPOINT project (now referred to as REPOINT1) was initiated in 2011 by the United Kingdom’s RSSB (Rail Safety and Standards Board) as part of a call for proposals titled: ‘Railway Capacity: overcoming the constraints caused by nodes (stations and junctions) on the rail network'. REPOINT was one response to that call, to examine whether the redundancy and fault-tolerant concepts which are readily accepted in other safety critical environments could be used beneficially for track switching on railway networks. The project set out to answer the research question:

‘Could a fundamental re-think of railway track switching ease some of the current route-setting constraints to provide higher capacity, and provide a significant reduction in operational unreliability arising from points failures?’

REPOINT proposed that due to the critical nature of operations at nodes, they require some built in redundancy to faults - fundamentally changing the nature of a junction to result in higher reliability of the individual assets and improved capacity. The capacity improvement comes partly from the reliability improvement and partly due to changes in the operating rules that become possible when the switches are redesigned to be intrinsically safe. The capacity benefits of re-engineering switches have been previously published by the authors, for instance in (8, 9).

Another significant output of this project was concept design for a novel arrangement of track switch, which enables this multi-channel approach. This switch uses multi-channel actuation elements, in a similar manner to aircraft flight control surfaces, and has the potential to provide the improved switch performance discussed in (8, 9). 'Performance', in this instance, refers to reduced lifecycle cost, increased availability, and improved maintainability. A detailed design of this proposal is available in more detail within the associated patent disclosures (10, 11). The concept design utilises four principles novel to track switching design, some inspired by the aerospace and nuclear industries: the LRU (Line-replaceable unit, as formally defined in standard MIL-PRF-49506 (12), mission-critical subsystem redundancy, fault tolerant control, and model-based condition monitoring. These have been combined with an idea fundamental to the rail sphere: Design-safe operation.

There currently exists a knowledge-gap regarding the practical implementation and operational aspects of this novel design. To bridge this gap, and move towards a prototype design, REPOINT 2 Phase 1 was initiated in May 2013 with the goal of constructing a functioning laboratory scale demonstrator. This demonstrator is now complete and fully operational in the control systems group laboratory at Loughborough University.

3 NOVEL TRACK SWITCHING ARRANGEMENT

The general layout of the 'traditional' design of track switch is well discussed in literature (See for example 1, 2) and is not included here for brevity. Generally, upon request from the signalling system, a single actuator moves two switch blades via a linkage, before locking the blades in place and communicating the detected position of the blades and lock back to the interlocking. In some installations there are multiple actuation units, or power take-offs known as 'back-drives' to ensure the entire movable length of blade moves correctly, however this is not multi-channel redundancy. Trains can be issued a movement authority (either by radio in communication-based signalling systems, or else by a line-side signal aspect) to pass the switch only once the correct detection signal is received by the interlocking. Movement of the switch blades normally takes several seconds. Around 8 seconds is allowed in British signalling practice, see, for example (13) for a more detailed discussion of switch control). As a switch represents a derailment danger when between positions and/or unlocked, the interlocking prevents signals being cleared in this state, and thus a service-affecting failure may ensue after a subsystem failure in any one of the elements listed above.

Adding multi-channel actuation to a track switch is non-trivial, as unlike the example of flight control surfaces, there is a requirement for the switch to be locked in a particular position for passing traffic (14). This essentially means each actuator must act through a common locking mechanism (and therefore a single point of failure), or else be able to unlock all other elements in the bank (perhaps necessitating an increasingly complex trackside mechanism as the number of actuation elements grows – with all associated maintenance issues). REPOINT has devised – and has patent pending upon – a simple yet novel arrangement referred to as 'passive locking', which overcomes these issues and for the first time may enable parallel multi-channel, actuation of track switches.

The actuation arrangement and passive locking could be applied to a traditional design of track switch, or more radically, a stub switch – the general layout of which is shown in figure 1. Use of a stub switch eliminates several of the more common failure points and modes of traditional track switches, including blockages between the switch and stock rails. However, practical engineering knowledge of stub switches upon a modern railway is limited, so additional development work would be required to bring this design to a deployable state. The stub switch reverses the traditional arrangement of 'heels' and 'toes', as described in (1), and utilises full-section rails throughout. It also allows arrangements with more than two routes from a single switch, impossible with the traditional design. All work described here on in in is related to the stub switch.

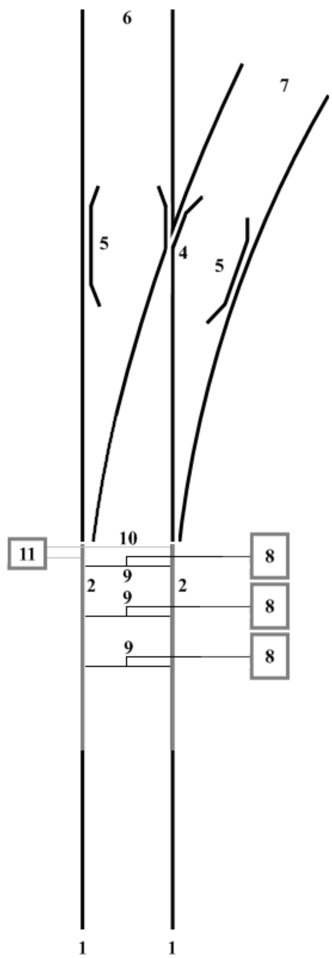

Figure 1: Proposed high-availability stub-switch concept with redundant actuation paths. 1 (Black, Bold) Stock Rails; 2 (Grey, Bold) Moveable Switch Rails; 4 Common Crossing; 5 Check Rails; 6 Straight Route; 7 Turnout Route; 8 Multi-Channel Actuators; 9 (Black) Drive Rod and Linkages ; 10 Detection Rods ; 11 Blade Position Detection and Feed-back Unit. Reproduced from (9)

Actuation elements and passive locking elements are located in bearers along the movable length of rails, termed ‘Actuator-bearers’. All elements are connected to a trackside cabinet, with a processor in a layer abstracted from the signalling system, capable of isolating (but crucially not commanding movement from) individual actuation elements should the in-built condition monitoring suspect an incipient fault. Individual elements can also be isolated by visiting repair teams, such that minor repairs can be effected whilst the switch is still allowing traffic to pass.

Each actuation element consists of a hollow bearer containing line-replaceable motor/gearbox unit, and a minimal set of five moving parts. The general arrangement of these moving parts is shown in figure 2. The motor/gearbox transmits power to a sliding, toothed actuation rod through a gearhead arrangement. This rod has further teeth meshing with two cams, the lobes of which engage with the underside of a component referred to as the ‘hopper’. When the rack moves, the cams are forced to rotate. A 180-degree movement of the cam effects a change of route by firstly lifting the rails before traversing them, and lowering them in a second position, in a semi-circular arc. When in the lowered position, the hopper sits upon a set of ‘locking blocks’ – essentially machined and matched mating protrusions on the underside of the hopper, and base of the hollow bearer, preventing any lateral or longitudinal movement of the hopper. The general arrangement of these blocks is shown in figure 3. This figure shows a 3-position REPOINT bearer, as per the laboratory demonstrator. The mass of a passing vehicle is also transmitted to the bearer casing, and thus ballast, through these blocks. When lifted, the hopper is free to move laterally, but not longitudinally. In order for the design to offer full passive safety, the force required to back-drive the motor must be less than that provided by the bending of the rails in the vertical plane. This will ensure that if there is a power loss during motion, the switch will fall back down to a safe, locked state. The lifting motion is also critical for the parallel-channel actuation:- each actuator bearer is capable of moving the switch alone, as each is capable of lifting the rails alone, the action of which will unlock all other actuator bearers.

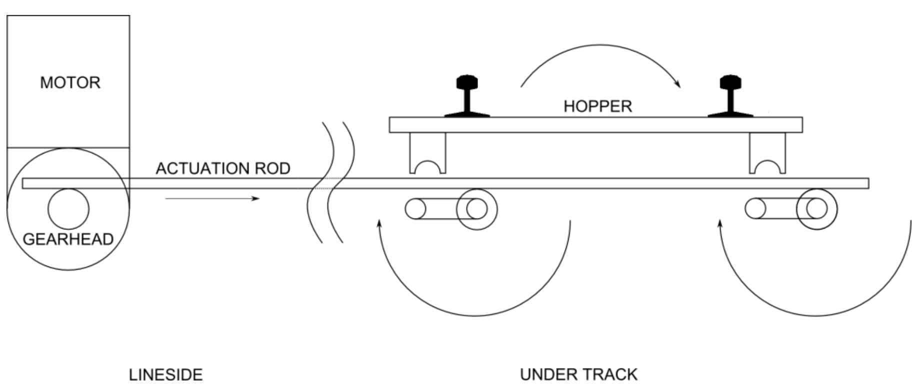

Figure 2: Mechanical transmission elements of each actuator-bearer unit

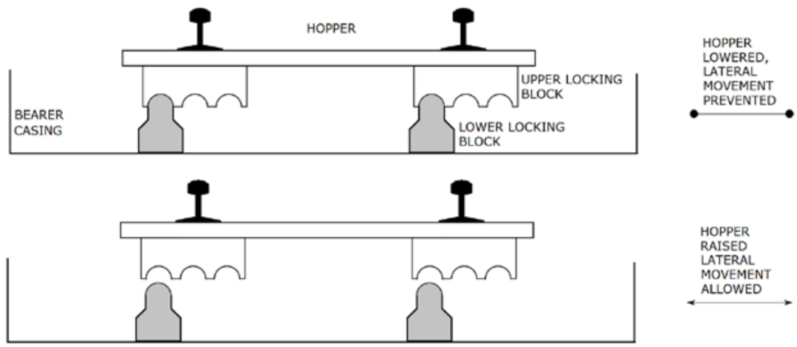

Figure 3: Passive locking elements of each actuator-bearer unit

4 MODELLING AND SIMULATION

For reasons of available space, it was proposed that the laboratory demonstrator be constructed at 384mm gauge. This is the gauge of the RHDR (Romney, Hythe and Dymchurch railway) in Kent, which has been identified as a possible technology demonstrator site for the next phase of development. This meant that the system modelling tasks were twofold. Firstly, to ensure a switch at this gauge was plausible, and to size the actuation units accordingly. Secondly, to model a standard gauge switch to ensure that the design would scale, and that bending full-section rail over the length of a typical NR (Network Rail) installation is plausible. NR-type switches, of lengths 'C' and 'F', were identified by NR as being examples of common short, station-throat type and long, high-speed types, respectively.

Initial appraisal and static calculations showed the dominant force through the actuation phase was bending of the full rail section in the vertical plane. Using Macaulay's technique, the rail pair are treated as a cantilever beam from a reaction anchor point (R_A), as shown in Figure 4. For a triple-redundant system, three actuation forces (P_{1-3}) were then applied, resisted by the uniformly distributed weight of the rail (q) and hopper/rail mounting masses (B_{A1-3}). The goal was to create a particular vertical rail stub toe deflection, which for a semi-circular tip actuation path equates to half the rail spacing between adjacent routes. Each actuator-bearer needs to be able to operate the switch alone for true triplicate redundancy. Therefore, the force requirement for each actuator bearer is simply the maximum of (P_{1-3}), plus a margin. Give the peak force requirements, the switching time of a given arrangement can then be calculated for any given power supply.

The resolved forces for both RHDR and NR type switches were not only remarkably close to each other, but also to those developed by existing switch designs. The effect of larger section – and therefore stiffer - CEN60 rail of the NR example was balanced by the much longer turnout radius and therefore effective beam length. This offered the opportunity to construct a 384mm gauge bearer, but with a motor and drive correctly sized for a NR example. The results of this modelling are shown in Table 1.

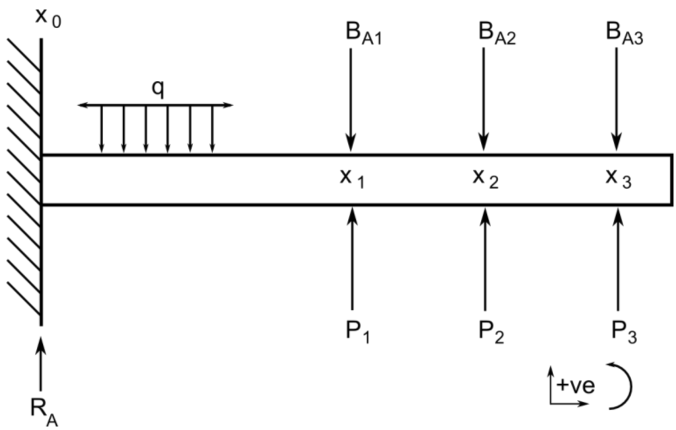

Figure 4: Simple beam equation for switch simulation and bearer interaction

	RHDR (384mm)	NR (C - type)	NR (F – type)
Natural switch length(mm)* / angle	4500 / 10	11900 / 9.25	20800 / 18.5
Movable rail length (Repoint, mm)	5000	7800	15800
Tip deflection (Horizontal) (mm)	120	100	100
Tip deflection (Vertical) (mm)	60	50	50
Resultant rod load, peak (N)	950	1380	920

Table 1: Results of rail pair bending simulation (*defined here as toe to heel)

Once feasibility was established, a more complex mathematical system model was created using the MATLAB/Simulink environment. This model was derived from a first principles physical analysis of the component parts of a REPOINT actuator-bearer. The objective was to provide an easily accessible, transparent description of the physical behaviour of a switch. Different switch installations may have differing parameters, but the model and interaction of the subcomponents will remain the same. As such, the structure of the model mirrors the physical structure of the plant. The structure of the model is shown in Figure 5. It has five main components: the brushless DC (BLDC) motor model, the gearhead model, the mechanical linkage model, the cam and hopper model, and a rail pair model linking each actuator bearer model, as described above. Figure 6 shows an example plot of load force vs cam angle for an RHDR switch example, as listed in table 1 and shown in Figure 7. The vertical load force is clearly dominant over the horizontal load, as would be expected when bending rail – an I-beam- in this manner. The resultant load curve represents the force required on the actuation rod in order to drive the cam. Due to the nature of the semi-circular actuation path providing a variable force vector, peak load on the rod is generally only around half of that required to move the switch. Note also that the total power requirement, which is proportional to the area under the resultant load curve, sums closer to zero than the total power transfer, which can be deduced from the sum of areas under the vertical and horizontal load curves. This is due to the motor optionally acting as a brake in the second half of actuation, when the force requirement turns negative as the spring and weight of the rails tends to force the switch back into a locked (lowered) position.

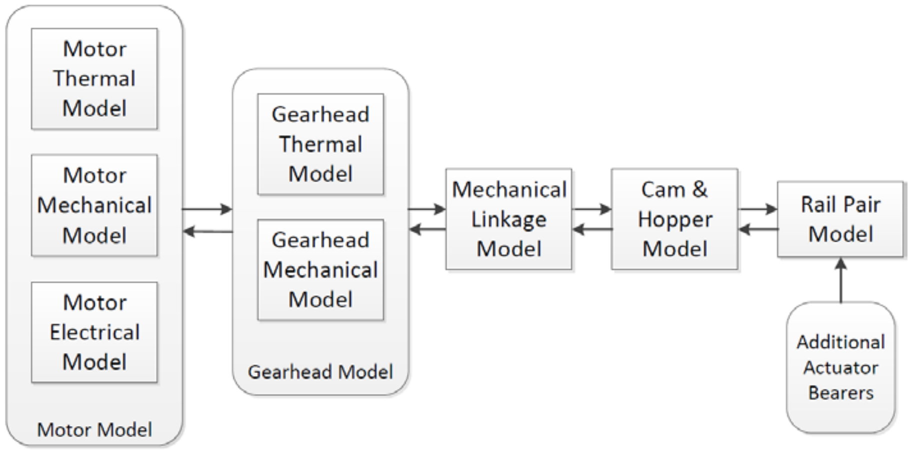

Figure 5: Whole-switch simulation schematic

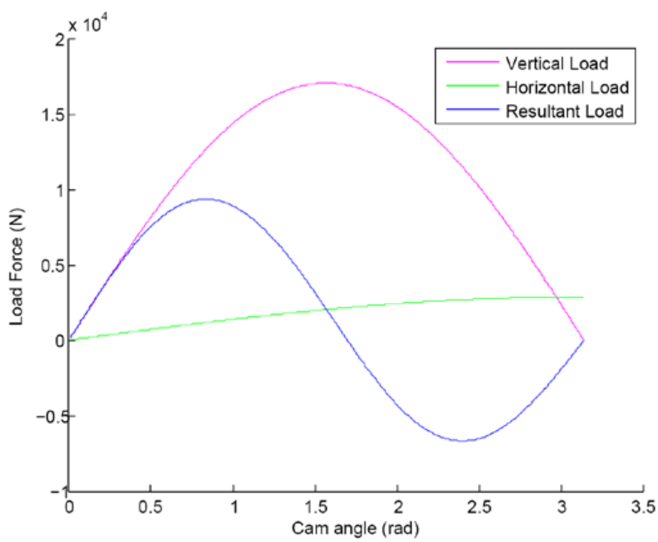

Figure 6: Example switch loading during actuation cycle (RHDR example)

The model was utilised in the model-based design process in order to correctly size components. However, it would also provide the basis for a co-simulation of actuator-bearers in the laboratory demonstrator, as well as a fundamental part of the model-based condition monitoring scheme of the functioning bearer. Extensive mathematical detail of each modelled element is described in (15) alongside sample outputs demonstrating load forces for particular switch arrangements.

5 LABORATORY DEMONSTRATOR

Using the results of this modelling exercise, a laboratory scale demonstrator has been designed and constructed. As of September 2014, the demonstrator is complete and undergoing a period of shakedown testing. The demonstrator consists of a control panel and mock signalling interface, a real-time processor, mock trackside power supply, single actuator bearer unit, and single bearer with machined stub rail ends for a 3-route switch. Figure 7 shows a view of the arrangement of demonstrator components in the laboratory. Figure 8 shows a close-up view of the first practical implementation of the passive locking arrangements described in figure 3.

For the first demonstrator iteration, Dexion bracing was used to connect the individual mechanical parts of the bearer. These parts were designed to fit inside a typical RHDR bearer envelope. Currently, only a single actuator-bearer unit has been constructed, which forms bearer number nine in the demonstrator layout shown in Figure 6. Actuator-bearer units seven and eight are software simulations using the model derived in section 4, and parameters established through testing the real unit, which run in conjunction with the physical mock-up when the switch is commanded to change position. These co-simulations run on the real-time D-Space processor unit.

As intended for a mainline installation, the demonstrator utilises COTS (Commercial off-the-shelf) components and technology wherever possible to keep costs relatively low. As such, the motor and gearbox are sealed units on an industry standard mounting pattern. The drive rod and all gears are standard sizes. The machined rail ends are held to the hopper and static bearer using Pandrol e-clip type clips, though the type of rail mounting is not critical to the function of the unit.

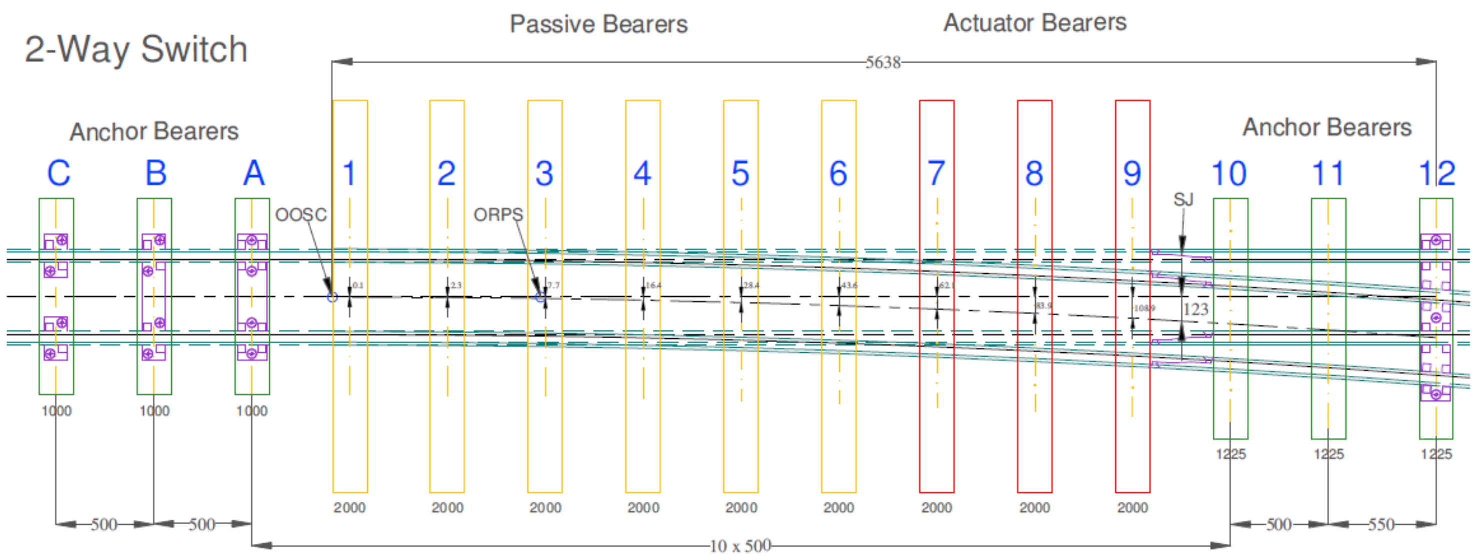

Figure 7: 384mm gauge switch layout as in laboratory demonstrator

ORPS: Original Real Point of Switch

SJ: Switch Joint

OOSC: Original Origin of Switch Curvature

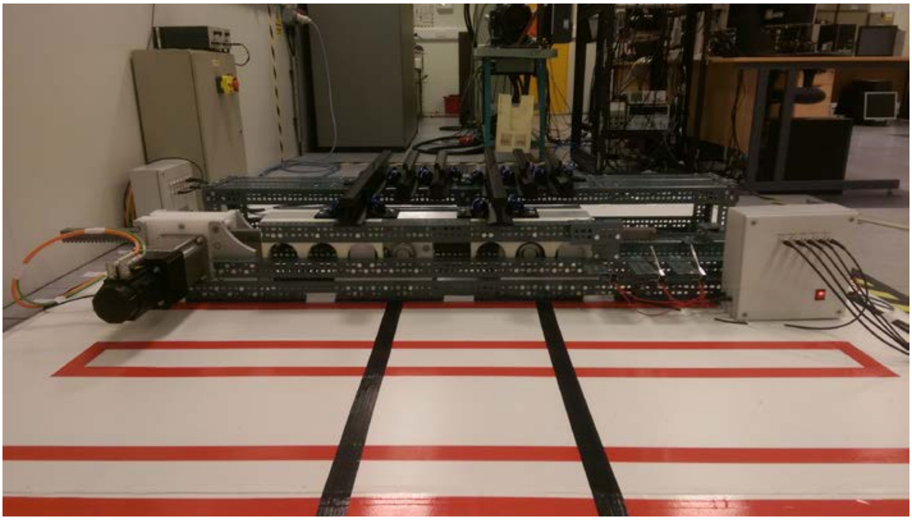

Figure 8: 384mm scale actuator bearer in laboratory

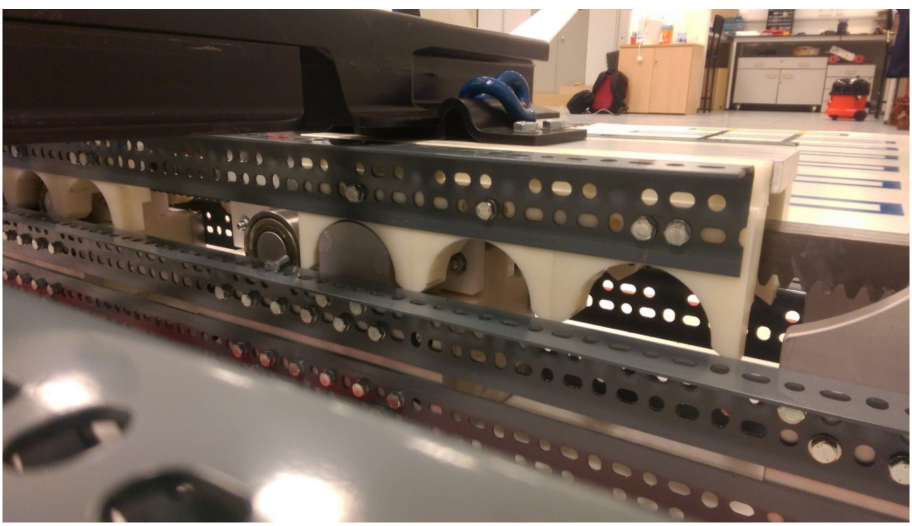

Figure 9: Close up photograph of actuation cam and locking block protrusions

The switch is actuated through a computer mock-up of an NX-type signalling panel. The computer has various other displays to demonstrate what information could be presented to different stakeholders – for instance local maintenance teams, or central asset managers.

6 CONCLUSIONS AND NEXT STEPS

This paper has introduced a novel mechanical arrangement of railway track switch which is under development as part of the REPOINT project at Loughborough University. The background to the project, the theory behind the novel design and the design features have been covered in some detail. The modelling and simulation of the design has been described, and the layout of the laboratory demonstrator shown. The demonstrator is now functional in a laboratory at Loughborough University.

The next phase of REPOINT is to take the general demonstrator arrangement, and complete a prototype installation with triplicate redundancy at a suitable test site. This test site may be at scale or standard gauge.

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REFERENCE LIST

1. Morgan, J. C. *British Railway Track 7th Edition, Volume 1, Design Part 2: Switches and Crossings.* Derby, UK: The Permanent Way Institution; 2009.
2. Cope, D. D. L. , Ellis, J. B. *British Railway Track 7th Edition, Volume 5: Switch and Crossing Maintenance.* Derby, UK: The Permanent Way Institution; 2002.
3. ORR (Office of Rail Regulation) Online Data Portal - Total journey count reporting (Accessed 2013-10-12) http://dataportal.orr.gov.uk/displayreport/report/html .
4. Network Rail. *"Network Rail October 2007 Strategic Business Plan Supporting document:- Seven Day Railway"*, Technical report, October 2007.
5. Institution of Mechanical Engineers, *"Rail Freight: Getting on the Right Track",* Technical report, Institution of Mechanical Engineers, February 2009.
6. Isermann, R. , *Fault-Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance*, Springer, Berlin, 2006.
7. Cribbens, A. H., *Solid-state interlocking (SSI): An integrated electronic signalling system for mainline railways.* P102-112, Electric Power Applications, IEE Proceedings B, 1987.
8. Bemment, S., Dixon, R., Goodall, R., "*REPOINT Redundantly Engineered Points for Enhanced Reliability and Capacity of Railway Track Switching*", in Proc.10th World Congress on Railway Research (WCRR). Sydney, Australia, November 2013.
9. Bemment, S., Dixon, R., Goodall, R., Brown, S., "*Redundantly Engineered Track Switching for Enhanced Railway Nodal Capacity*", in Proc. 1st IFAC ACATTA Workshop. Istanbul, Turkey, September 2013.

10. (Patent) Loughborough University, "Railway points operating apparatus (GB 1322660)", 20 December, 2013.
11. (Patent) Loughborough University, "Railway points (GB 1322641)", 20 December, 2013.
12. US Army. *MIL-PRF-49506 US Military Specification: Performance Specification:- Logistics Management Information*, November 1996.
13. Hadaway, H. W., *IRSE `Green Booklet' no.5:- Principles of power point control and detection (British Practice).* The Institution of Railway Signal Engineers, London, 1950.
14. Genner, R., *Railway Group Standard GK/RT0062: Control Of Points.* London, 1997.
15. Wright, N., Bemment, S., Ward, C., Dixon, R., *A Model of a Repoint Track Switch for Control,* Proceedings of UKACC International Conference on Control, Loughborough, UK, June 2014.