

Railways Discovering Mechatronics and Monitoring – An Overview

Roger Goodall*, Roger Dixon**, Moussa Hamadache**, Christopher Ward***

*University of Huddersfield, HD1 3DH, UK (e-mail r.m.goodall@hud.ac.uk)

**University of Birmingham, B15 2TT, UK (email r.dixon@bham.ac.uk)

***Loughborough University, LE11 3TU, UK (email c.p.ward@lboro.ac.uk)

Abstract: The railway industry has been significantly slower than the competing modes of air and road in taking advantage of mechatronics and health monitoring, although a number of possibilities are now “hot topic” research areas being considered worldwide. This paper describes some current research work and a range of opportunities ranging from “low level” (vehicle sub-systems) through to “high level” system wide benefits.

Keywords: Rail vehicle, rail infrastructure, rail control, mechatronics, condition monitoring

1. INTRODUCTION

Railways worldwide are not only accepted as an essential part of national infrastructure but also contribute significantly to a sustainable future. Railways use narrow corridors of land to give extremely safe, high capacity transport. Many existing and almost all new railways use electric trains, and the “green credentials” of railways are well founded, albeit this is under challenge from competing transport modes, especially as a result of the improvement in automobiles. However, unlike automobiles, electric trains are already grid-connected and therefore able to take advantage of the progressive decarbonisation of national energy supplies, which gives them a significant “head start” over electric road vehicles from a sustainability viewpoint.

Despite this “unique selling point”, in many countries the price to passengers and the cost to government in terms of subsidy are a disincentive to achieving a much larger market share, added to which many critical parts of existing networks are already operating close to maximum capacity. Also, passengers’ expectations in terms of flexibility, quality and reliability of service inevitably rise as time goes on. Consequently, railways must face some key challenges in order to deliver their potential into the future. Europe in particular has ambitious technical strategies aimed towards meeting these various challenges (see e.g., Shift2Rail (2018), and UIC (2019)). In the UK, the industry have published a summary 30 years vision for the industry (Network Rail (2019)) and industry groups have proposed the capability delivery plan in order to motivate and deliver the Research & Development (R&D) agendas, as summarised by Mungo 2017. The 12 key capabilities agreed on for the UK are common with the EU vision. A summary diagram can be seen in Fig. 1, the capabilities include: (1) Running trains closer together, (2) Minimal disruption to train services, (3) efficient passenger flow through stations and trains, (4) More value from data, (5) Optimal energy use, (6) More space on trains, (7) Services timed to the second, (8) Intelligent trains, (9) Personalised customer experience, (10) Flexible freight, (11) Low-cost railway solutions, (12) Accelerated research, development and technology deployment.

The last is obviously overarching, but most of the capabilities can be underpinned by research and innovation in mechatronics, monitoring and control. Hence the opportunities are both broad and deep for research in these areas.

The paper will summarise how mechatronic and condition monitoring principles might be applied to vehicles, infrastructure and system control. A few motivational examples are given, but this is not a thorough review of everything emerging in this area – as that will be self-evident from the papers within the special invited track of which this paper is but one. This paper uses many of the ideas presented in (Lamnabhi-Lagarigue et al (2017)).

2. NEW TECHNOLOGIES

Alongside the industry and governmental drivers to research mentioned above, there are a number of technologies that have emerged over the past decade which invite railway researchers and engineers to exploit them to deliver a “smarter” mechatronic railway. Perhaps most important among these are: advances in power electronics, motors, drives and actuators, sensing and communications and emergence of the concepts of big data and the internet of things (IoT).

2.1 Power electronics

Developments in power converter technology have enabled a fundamental transition from DC to AC motors, which are lighter, more compact, more efficient and more reliable. It has also led to the transition from locomotive-hauled trains to trains with distributed traction, i.e. where most or all vehicles have their own traction equipment.

2.2 Drives and actuation

Recent developments in motor technology, driven (predominantly) from the drive for more electric aircraft and electric/hybrid vehicles, are yielding smaller motors with higher torque and speed from smaller packages. This is in part linked to the improved ability to regulate voltage and current to these devices due to improved sensing and power electronics.



01. Running trains closer together 02. Minimal disruption to train services 03. Efficient passenger flow through stations and trains
 04. More value from data 05. Optimum energy use 06. More space on trains
 07. Services timed to the second 08. Intelligent trains 09. Personalised customer experience
 10. Flexible freight 11. Low-cost railway solutions 12. Accelerated research, dev. & technology deployment
 Fig. 1. Showing the 12 key capabilities for a future railway (Network Rail (2019)).

Furthermore, motor and drive technology is also leading to a wider range of actuators including electromechanical actuators (EMA) with ball/leadscrew, linear motors, electrohydraulic actuators and a plethora of novel Micro-Electro-Mechanical systems (MEMs) micro-actuators and concepts such as high redundancy actuation (Du et al. (2010) and Biju et al. (2019)). These provide the opportunity to rethink drive and actuation through-out the railway, and to introduce it in places where in the past it was not viable.

2.3 Communications technology, IoT and computing power

Developments in the ability to communicate and process data have been significant in the past two decades. To the point where the Internet of Things is beginning to become a reality in some areas such as the military and home automation. The opportunities of pervasive intelligent systems and the ability to generate useful information to support the operational and maintenance optimisation of railway systems is now greater than ever before. Of course there remain many challenges with data ownership, provenance and cyber-security.

3. MECHATRONICS FOR THE VEHICLES

There are a number of possibilities for intelligent mechatronic systems on railway vehicles, but here the focus is upon those that can have a major impact at the overall system level: principally power control and energy storage, which are

related to improving energy efficiency; this can be further enhanced by smart monitoring and control leading to more efficient driving/operation at the vehicle level through braking and acceleration profiles that can be optimised in real-time.

There are a number of mechatronic solutions for the suspensions and running gear, most immediately related to providing improved “track-friendliness” of the vehicles, but also to facilitate simpler, lighter mechanical configurations that are currently not achievable. As will be explained in subsection 3.2, advanced mechatronic rail vehicles can potentially give significant operational benefits leading for example to substantial reduction in track access charging.

3.1 Electric drives

Electric trains are already widely available and technologically mature, and for this reason are in an excellent position to take full advantage of progressive decarbonisation of the national energy generation facilities, and therefore well-placed to maintain their position as the most energy-efficient form of ground transportation. Because braking is a safety-critical function, all trains currently still require conventional friction brakes. However anticipated developments in energy storage technology will lead to devices that are usable on trains in terms of energy densities (both mass and volume) – see Fig. 2.

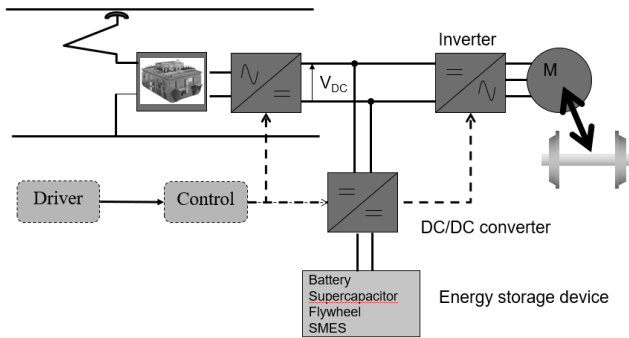


Fig. 2. Advanced power control scheme.

This will not only enable further improvements in energy efficiency, but also bring the possibility of wholly electrically-braked trains, i.e. no friction brakes. Energy storage combined with future developments in power converters will therefore provide the opportunity to optimise the energy management by altering the flow of energy between the trackside power supply, the traction motors and the energy storage devices, including accommodating the need to both maintain the timetable and minimise energy via smart driving control – a challenging multi-objective mechatronic optimisation problem.

3.2 Suspensions and running gear

The idea of “design for control” has already been extensively employed in the aerospace and automotive industries, which has proven highly beneficial. Aircraft and cars are now significantly different mechanically to what they were 40-50 years ago, whereas the conventional structure of rail vehicles (a carbody suspended on two bogies (sometimes called trucks), each with two solid-axle wheelsets) is substantially unchanged. Mechatronic concepts for rail vehicles are now on the research agenda in a number of countries, and this will enable a fundamental re-think not only of some of the traditional design trade-offs, e.g., between running stability and performance around curves, but also proper mechatronic solutions giving new mechanical solutions leading to simpler, lighter, more energy-efficient and track-friendly vehicles as illustrated by Fig. 3 (Goodall and Ward (2014)).

4. MECHATRONICS FOR THE INFRASTRUCTURE

The infrastructure itself is mostly passive so the opportunities for mechatronic solutions are limited. Hence most of the mechatronics-related innovations relate to infrastructure condition monitoring (see Section 6).

A significant exception is the track switches, which are moving components acting under the influence of the train control system. There are a number of innovations in this area reaching the point where industry could pick them up, for example: REPOINT (Bemment et al. (2017)), where the aim is to incorporate redundant actuation and fault-tolerant control principle; and the “Winterproof Turnout” (WIRAS (2018)), which uses innovative actuation with the aim to remove the need for heaters.

Other research includes recently completed projects such as S-CODE (S-CODE (2018)) and INTELLISWITCH (INTELLISWITCH (2019)), also current projects such as IN2TRACK2 (IN2TRACK2 (2019)). These projects between them cover novel actuation and monitoring for switches (particularly Intelliswitch). In the limit the actuation side can be removed entirely with mechatronic vehicles offering the potential for steering through switches as proposed in S-CODE and (from the vehicle side) by Farhat et al. 2018.

5. MECHATRONICS FOR SYSTEM CONTROL

Rail traffic management involves both a safety layer and a management layer. The safety layer ensures safe separation of trains, traditionally by means of lineside signals protecting fixed blocks of track. Ensuring that only one train is in any block provides a safe stopping distance to a following train in the case of a problem with the preceding train, and the signals also protect the approach to track switches, junctions and stations. The principal challenge is the very high integrity level required to preserve the safety standard: railways have traditionally worked upon a “fail-safe” approach so that if anything goes wrong all the relevant trains are stopped, but this is generally not consistent with achieving high reliability.

The management layer involves an agreed operational timetable to determine normal operation, combined with automatic route-setting in localised regions around nodes (junctions, stations etc.), by which common train movements

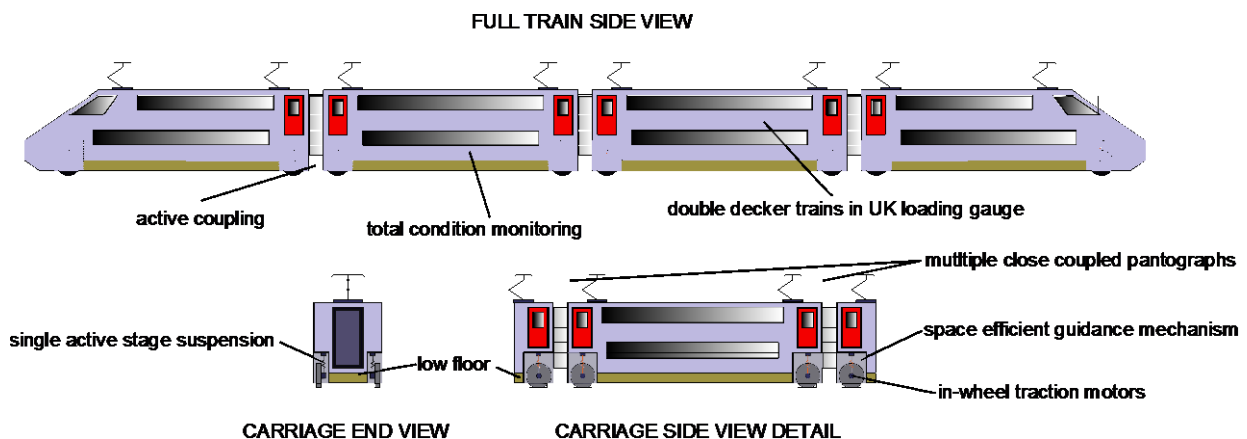


Fig. 3. “Design for Control” concepts (Goodall and Ward (2014)).

are fully automated according to a predetermined schedule or script. Although control used to be localised in signal boxes etc., nowadays overall control has progressively become centralised into control centres covering many kilometres of the surrounding network. The location of the trains is generally via track-based techniques such as track circuits and axle counters which send information directly to the control centre. The trains themselves are therefore essentially “dumb”: train drivers have to obey running instructions from the lineside signals, although in some cases these are repeated within the driving cab.

The theoretical capacity for a plain line (e.g., trains per hour, or the “headway” times between trains) can be calculated, but as soon as there are any fixed nodes (principally stations and junctions) this theoretical level is not achievable, and in practice capacity is very difficult to quantify, which means that the design of the operational timetable in order to accommodate the greatest number of trains is a complex process. Also, there is a trade-off between capacity and reliability: attempting to operate very close to maximum capacity means that even minor problems with the track or trains may create large disruption as the effects propagate around the surrounding part of the network (i.e., the railways’ equivalent of congestion on roads). For this reason, railways typically aim to run at around 70% of maximum capacity.

5.1 Moving block train control

An important step, which is emerging, is to move away from lineside signals and create “moving blocks” behind each train – see Fig. 4. Each train must communicate its position, measured by a combination of track balises, global positioning system (GPS) and odometry, to a central control, which sends back a speed command for the train – the European Rail Traffic Management System (ERTMS) is an example of this (ERTMS (2019)).

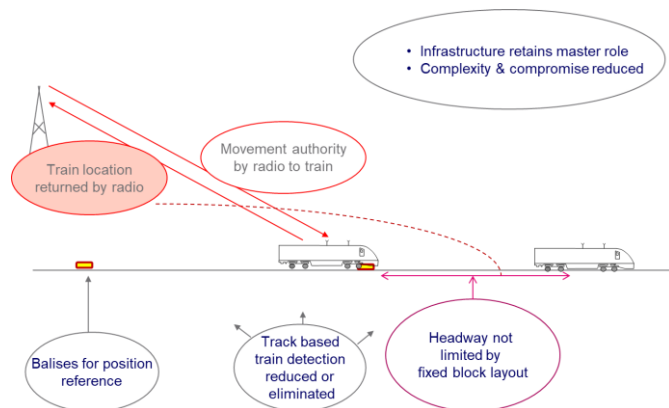


Fig. 4. Moving block train control.

It’s possible to extend this idea by arranging for a number of trains, which are taking the same path through junctions to operate as a convoy. The lead train will retain the centralised communication and control of normal moving block, but subsequent trains will have inter-train communication so that they can maintain an appropriate spacing to the preceding train.

5.2 Advanced moving block solutions

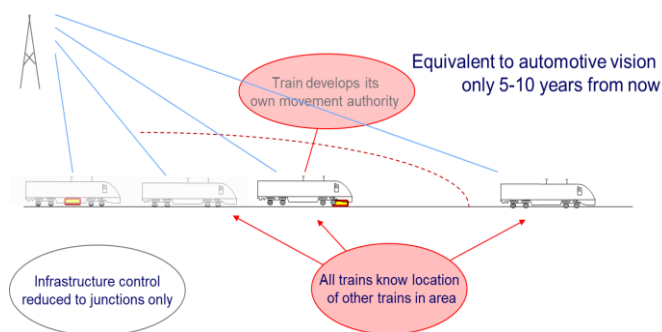


Fig. 5. A concept of advanced moving block solution that gives more autonomy

Figure 5 illustrates a concept in which all trains are aware of the presence, position and speed of other trains in the area, and therefore control themselves to maintain a safe distance. The central control knows the position of a large number of trains and is therefore able to control operation of and control through junctions so that network management can be facilitated using sophisticated optimisation strategies.

Figure 6 illustrates a further step in the level of autonomy in which the trains also assume control through junctions by “negotiating” with trains that require passage through the junction – the diagram indicates the kind of criteria that might be utilised as part of the negotiation.

Overall then it’s clear that mechatronic solutions at a system level have the potential to take system control technology substantially beyond the current state-of-the-art.

Increased autonomy

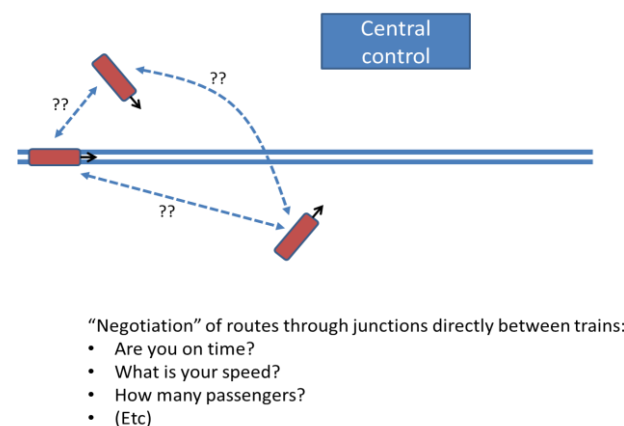


Fig. 6. Autonomy at junctions.

6. CONDITION MONITORING IN RAIL

The industry is keen on condition monitoring (CM), in particular to enable condition based maintenance (and reduce costs while improving system level reliability). CM techniques that are facilitators for implementing a condition-based preventive maintenance strategy, allows an optimal utilization of component lifetime while avoiding unforeseen failures and costly advanced-stage damages (Coronado and Fischer (2015)). Further, it may even allow to completely prevent the

emergence of damage, which lead to lower repair cost, but also facilitates better maintenance planning and minimises the related revenue loss (Ahmad and Kamaruddin (2012)). As can be seen in Fig. 7, the corrective maintenance strategy benefits the employment of the whole component lifetime, but the risk of secondary damage or even catastrophic failures is high. The predetermined preventive maintenance has the advantage of being scheduled, but the waste of life in cases where the components could last for a longer period can make it an expensive option. In case of the condition-based preventive maintenance that aims for early fault detection followed by preventive measures, severe damage of the monitored component and damage propagation to other components can be avoided. Therefore, it is a need nowadays for the railway industry stakeholders to adopt and incorporate the CM technology to minimize the disruption caused by activities such as inspection, remedial, remove and corrective maintenance, and track renewal (Ngigi, et al. (2012)), especially with the age of the IoT.

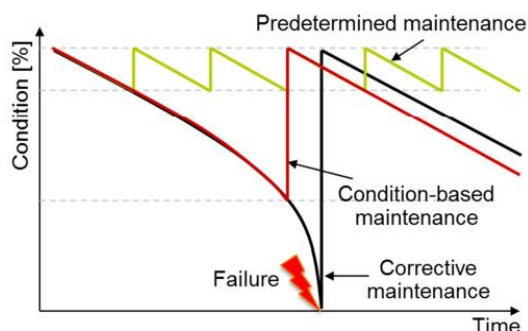


Fig. 7. Influence of the maintenance strategy on asset condition (Coronado and Fischer (2015)).

A railway system is a highly complex Mechatronic system that has two main parts, the railway tracks and the vehicles, without forgetting the signalling system, structures (e.g., tunnels and bridges), stations (platforms), embankment, and the drivers (staff). A number of techniques have been and will be utilised to perform CM in railway system that must capture and cover all the pre-mentioned parts for example, either for monitoring the dynamics of the railway vehicle (Roberts, et al. (2019)), or monitoring the railway switch and crossing (S&C) health status (Hamadache et al. (2019a and b), (Dutta et al. (2020))). Currently in practice, the existing CM technologies in the railway industries are implemented either on-board (vehicle-based) or track-based techniques as can be seen in Fig. 8 (a) and (b), respectively.

Implementing these CM solutions on a railway vehicle system for instance, require assessing extra features such safety and reliability. Thus, it is very critical to choose the right CM technique to be used that can handle severe nonlinear system, robustness, sensitivity to disturbances and computation performance (Ngigi et al. (2012)). Typical choices are physical/mathematical model-based CM techniques, the data-driven and/or shallow learning-based CM techniques, and/or the contemporary techniques that use deep learning CM

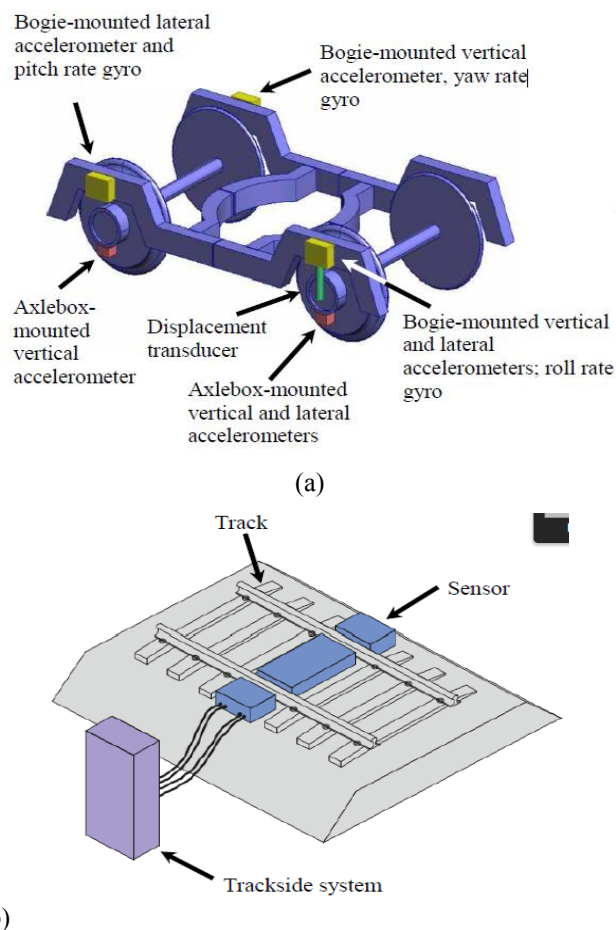


Fig. 8. Current implemented HCM technologies in railway: (a) Bogie and wheelset sensor position (Ward et al. (2011)), (b) Trackside sensor configuration (Ngigi et al. (2012)).

algorithms (Hamadache et al. (2019c)). Moreover, structural condition monitoring is an increasingly interesting topic for the industry (see e.g. S-CODE 2018).

7. A FUTURE INTELLIGENT MECHATRONIC RAILWAY?

It is clear that intelligent fault detection and condition based maintenance have a lot to offer for future railway systems, and indeed are already beginning to gain a foothold. However, in terms of control, the railway's current trend towards centralised control, albeit with information relayed directly to the train rather than via lineside signals, is contrary to the vision proposed by most researchers for future autonomous automobiles. Aircraft flight control centres are also very centralised although again, some researchers promote the idea of autonomous aircraft operation (Fig. 9).

This therefore raises key questions for railways: is it better to have an all-seeing, all-knowing, centralised control of operation, or to release the free-spirited, independent approach from full autonomy? Associated with these questions is how such ideas can be incorporated when the present system is in many ways still only halfway in their life cycle?

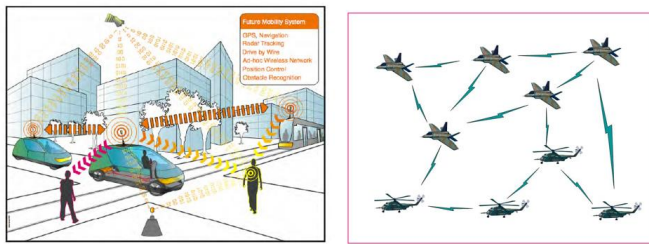


Fig. 9. Future autonomous automotive and aircraft concepts.

However current “free-spirited” human-driven automobile driving is substantially less safe than what is achieved in railways and flying: Is this because the fallibility of human decision-making, or the limited situational awareness? Would a future system in practice be constrained by a system authority and fail to deliver the kind of capacity improvements that some have predicted? These are big questions that would need to be addressed if full exploitation of mechatronic technologies for railways is to be achieved.

REFERENCES

- Shif2Rail, (2018), Multi-Annual Action Plan, available at: https://shift2rail.org/wp-content/uploads/2018/04/Maap_2018_FINAL_2.pdf. [Accessed Nov. 2019].
- UIC, (2018), Railway Technical Strategy Europe 2019, [online], available at: https://uic.org/europe/IMG/pdf/2019_uic_railway_technical_strategy_europe.pdf [Accessed Nov. 2019].
- Network Rail, (2019), Railway Technical Strategy Europe 2019, [online], at: <https://cdn.networkrail.co.uk/wp-content/uploads/2019/03/Rail-Technical-Strategy.pdf>
- Lamnabhi-Lagarrigue, F., Annaswamy, A., Engell, S., Isaksson, A., Khargonekar, P., Murray, R., Nijmeijer, H., Samad, T., Tilbury, D., Van den Hof, P. (2017). Systems & control for the future of humanity, research agenda: Current and future roles, impact and grand challenges. *Annual Reviews in Control*, 43(2017), pp.1–64.
- Mungo, S. (2017). Rail Industry Capability Delivery Plan, Rail News, [online] available at: <https://www.railengineer.co.uk/2017/02/16/rail-industry-capability-delivery-plan/> [accessed Nov. 2019].
- Du, X., Dixon, R., Goodall, R.M. and Zolotas, A.C. (2010). Modelling and control of a high redundancy actuator. *Mechatronics*, 20 (1). pp. 102 - 112. ISSN: 0957-4158
- Biju Prasad, B., Biju, N., and Radhakrishna Panicker, M.R. (2019). High redundancy electromechanical actuator for thrust vector control of a launch vehicle. *Aircraft Eng. and Aerospace Technology*, 91(8), pp. 1122-1132.
- Goodall, R.M., and Ward, C.P. (2014). Rolling stock technology for the future. *Presented at: International Conference on High Speed Rail*, University of Birmingham, 9 pages.
- Bemment, S.D., Ebinger, E., Goodall, R.M., Ward, C.P., and Dixon, R. (2017). Rethinking rail track switches for fault tolerance and enhanced performance. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 231(9), 1048–1065.
- WIRAS, (2018). The WIRAS Turnout Design, [online], available at: <http://www.winterproofturnout.info/>. [Accessed Nov. 2019].
- Switch and Crossing Optimal Design Evaluation (S-CODE) project, (2018) [online], available at: <http://www.s-code.info/>. [Accessed Nov. 2019].
- Intelligent Quality Assessment of Railway Switches and Crossings (INTELLISWITCH) project, (2019) [online], at: <http://www.intelliswitch.dk/>. [Accessed Nov. 2019].
- Research into enhanced track and switch and crossing system 2 (IN2TRACK2) project, (2019) [online], available at: https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2TRACK. [Accessed Nov. 2019].
- Farhat, N., Ward, C.P., Goodall R.M., and Dixon R. (2018). The benefits of mechatronically-guided railway vehicles: A multi-body physics simulation study. *Mechatronics*, 51(2018), pp. 115-126.
- European Rail Traffic Management System (ERTMS) project, (2019) available at: https://ec.europa.eu/transport/modes/rail/ertms_en. [Accessed Nov. 2019].
- Coronado, D.A., and Fischer, K. (2015). *Condition monitoring of wind turbines: state of the art, user experience and recommendations*. Project report, Fraunhofer Institute For Wind Energy And Energy System Tech. IWES, pages i.
- Roberts, C., Entezami, M., Stewart, E., Yeo, G., Peinado Gonzalo, A., Hayward, M., and Ainsworth, P. (2019). Continuous railway track monitoring using passenger trains. *In World Cong. on Rail. Research*. Tokyo, Japan.
- Hamadache, M., Dutta, S., Olaby, O., Ambur, R., Stewart, E., and Dixon, R. (2019a). On the fault detection and diagnosis of railway switch and crossing systems: An overview” *Applied Sciences*, 9(23), 32 pages. <https://doi.org/10.3390/app9235129>
- Hamadache, M., Dutta, S., Ambur, R., Olaby, O., Stewart, E. and Dixon, R. (2019b). Residual-based fault detection method: application to railway switch & crossing (S&C) system. *In the 19th International Conference on Control, Automation and Systems (ICCAS 2019)*, ICC Jeju, Jeju, Korea. DOI: 10.23919/ICCAS47443.2019.8971747
- Dutta, S., Ambur, R., Hamadache, M., Olaby, O., Shih, J.Y., Stewart, E., and Dixon, R. (2020). Health Monitoring Of a Railway Track Switch Actuator Based On Continuous-Time Parameter Estimation Method', 8th Transport Research Arena TRA 2020, Helsinki, Finland, 27/04/20 - 30/04/20..
- Ahmad, R., and Kamaruddin, S. (2012). An overview of time-based and condition-based maintenance in industrial application. *Computers & Industrial Engineering*, 63(1), pp.135–149.
- Ngigi, R.W., Pislaru, C., Ball, A., and Gu, F. (2012). Modern techniques for condition monitoring of railway vehicle dynamics. *25th International Congress on Condition Monitoring and Diagnostic Engineering, Journal of Physics: Conference Series*, 364, 13 pages.
- Ward, C.P. Weston, P.F. Stewart, E.J.C, Li, H., Goodall, R.M., Roberts, C., Mei, T.X., Charles, G. and Dixon, R. (2011). Condition monitoring opportunities using vehicle-based sensors. *Proc. of Inst. of Mechanical Engineers Part F: Journal of Rail and Rapid Transit.*, 225(2), pp 202–218.
- Hamadache, M., Jung, J.H., Park, J., and Youn, B.D. (2019c). A comprehensive review of artificial intelligence-based approaches for rolling element bearing PHM: shallow and deep learning. *JMST Advances*, 1(1-2), pp. 125–151.