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RELIABILITY RESEARCH ROADMAPPING WORKSHOP: IMPLICATIONS FOR ENGINEERING DESIGN

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Abstract

Transportation industries are the centrepoint for some remarkable transformations driven by technology development and innovation. However, we have seen limited advances on methods to address reliability and resilience challenges emerging with increasingly complex systems and environments. This paper presents the outcomes of an European Reliability Research Roadmapping workshop, collating the views of automotive, aerospace and defence industries to identify current reliability challenges and research gaps and to define directions for future research and skills development.

Keywords: reliability, robust design, complex systems, systems engineering (SE)

1. Introduction

We are witnessing remarkable transformations across the transportation industries driven by technology advancements and proliferation across the systems scales and boundaries. Technologies to support increased levels of autonomy as well as user centric service innovation are already commonplace in systems architectures. From the viewpoint of a product development organisation, handling the explosion of complexity induced by the heterogeneous nature of systems is a significant challenge, compounded by the pressure to develop systems in an environmental and cost conscious manner, with uncompromised levels of safety and dependability demonstrated against diverse, global usage scenarios.

While technology development has been the prime focus of research and innovation effort, we have seen only limited advances on methodologies and methods to address the reliability and resilience challenges emerging with increasingly complex systems and environments. Some of the challenges and opportunities in reliability engineering have been recently discussed by Zio (2016) and Coit and Zio (2018), while similar reviews have been provided for the related topics of risk (Zio, 2018; Favaor and Saleh, 2016) and resilience engineering (Righi et al., 2015; MacKenzie and Hu, 2018; Zhang et al., 2017). The merit of these works is that they attempt to reflect a trans-disciplinary viewpoint of the trends in the field, addressing the fact that most studies focus on a single discipline approach / viewpoint. Global approaches to reliability assessment of an entire system are relatively rare. For example, Gandoman et al. (2019) have provided a useful review of reliability assessment methodologies for electric vehicles, however, they have not considered systematically the connectivity and autonomous features. On the other hand, with much of the recent work focussed on the autonomous systems majoring on safety and dependability (Fitzgerald et al., 2016), the distinction

between reliability and dependability has become somewhat blurred. Kim and Smidts (2015) have provided some useful basic definitions of terms to support the joint safety and reliability analysis of digital systems, which set a good foundation to enable consideration of reliability alongside mission safety in the evaluation of the overall performance. Some recent examples of consideration of system reliability within a digital / cyber-physical system (CPS) include Schleiss et al. (2017), Castano et al. (2019), Yang et al. (2018), and Koopman and Wagner (2016). The SAE IVHM framework (SAE International, 2018) introduces a six-point scale for automotive and aerospace vehicles health capability levels, including intelligent self-management of systems health.
In order to facilitate the exploration of key reliability issues arising from recent technological developments, a one-day workshop was organised in May 2019 at the University of Bradford, bringing together industry and academia technical experts to identify the gaps in knowledge, methods and skills, and directions for fundamental and applied research. The workshop, sponsored by the Confederation of European Environmental Engineering Societies (CEEES), focussed upon three themes:

- ***Theme 1: Technology Development & Innovation***: What are the reliability challenges stemming from the accelerated introduction of new technologies?
- ***Theme 2***: ***Right First Time Through Design***: What reliability methodologies and methods are needed to better support Product Development?
- ***Theme 3***: ***Intelligent Systems Health Management***: What challenges need to be overcome for Machine Learning and AI to consistently underpin effective systems lifecycle management?

This paper presents the summary and analysis of the key outputs from this workshop along the lines of the three themes, reflecting on implications for engineering design research and practice.

2. Methodology

2.1. Reliability research roadmapping workshop

2.1.1. Workshop participants

In total, 27 participants attended the workshop, representing 16 organisations: 13 Companies from 4 European countries (UK, France, Netherlands and Sweden) providing 18 participants and 3 UK Universities (9 participants). Industry sectors represented included: automotive, aerospace, defence and marine. Automotive industry had the largest representation including OEMs (4 – three large car OEMs and one medium size electric vehicle OEM), global tier 1 automotive suppliers (4), and a global commercial engine manufacturer. The participants represented a broad set of engineering disciplinary expertise, including mechanical, mechatronics, electronics, chemical, computer science, and design.

2.1.2. Workshop process

The workshop aimed to provide a highly interactive format, combining panel sessions with small group round table discussions, and agenda setting activities. The workshop process is summarised in Figure 1, and was broadly followed for each of the three themes.

Figure 1. Workshop process

The "Panel Discussions" were scheduled to include two short agenda setting addresses (up to 5 minutes) from industrial experts (for each theme), outlining company and industry specific viewpoints of the

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challenges. For the "Round Table" (RT) discussions the participants were split into three groups of equal size and with a good mix in terms of industry / academic background, industry sector representation and engineering disciplinary expertise. The suggested Round Table process included three steps: (i) team based discussions to identify and record (on post-it notes) key issues from the perspective of each participant - i.e. based on their insight of the company / industry needs; (ii) for each issue (or thematic group of issues) identify and record the associated gaps in knowledge and / or skills; and (iii) for each issue and the associated gap, directions for research and skills development were identified.

Each team was provided with a metaplan board to organise the collected ideas and display the outcome of the discussions. For the "Summary" session, each RT team in turn presented the key outcomes from their discussions. Each presentation was followed by a short questions and answers with the whole group, to clarify ideas and explore linked items across teams. The summary presentations were audio recorded to be available for subsequent post-workshop analysis.

2.2. Post-workshop analysis

The workshop information available for the analysis included (i) the slides from the agenda-setting viewpoint presentations made by the six industrial panellists; (ii) the outcomes from the round-table discussion as affinity diagrams, including the ideas recorded on post-it notes, organised on topics; and (iii) audio recording from the summary presentations made by each group. The analysis followed the process outlined in Figure 2. The primary analysis, conducted by the lead author, re-considered the Round Table (RT 1-3) summaries from each theme based on the items listed on post-it notes and organised on themes. The audio recordings of the team presentations were considered, with additional annotations made to capture the important points not recorded on the post-it notes. The notes were typed up and organised using a mind-mapping software, generating initially a mind-map representation for each RT team. In a second phase, the common topics relating to challenges, gaps and directions were consolidated across the RT outputs, ensuring that all significantly different ideas were appropriately captured and associated with the relevant headers. On the basis of this consolidated summary, a brief report was generated for each theme, which was subsequently reviewed by the core workshop team - also cross-checking against the original records of the ideas captured during the workshop.

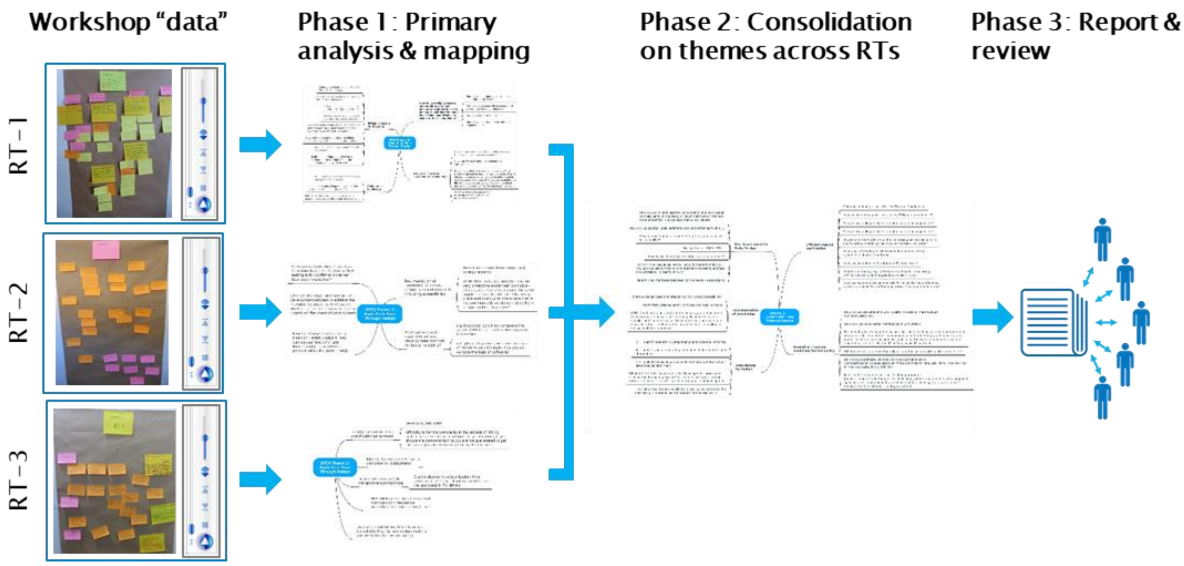

Figure 2. Post workshop analysis

3. Reliability challenges and research directions

3.1. Technology development and innovation

The key points discussed across the three RTs are discussed below and summarised in Table 1.

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Table 1. Technology Innovation - summary of challenges and research directions

Industry challenges	Research directions
How do we introduce new technologies with old systems?	Whole system multi-disciplinary reliability modelling – integrating multi-physics-of-failure models with communication and software systems risks Optimal system lifecycle sustainability: (i) Reliability and resilience modelling for evolving systems; and (ii) Optimal obsolescence planning and management.
Reliability challenges with the adoption of new materials, processes, technologies	Develop methods and standards for the fast testing / validation of new materials and technologies (including high power mechatronic and embedded systems). Use of AI to leverage engineering knowledge and physics based models with limited test data to predict risks.
Systematic consideration of Real World use uncertainty	Maintain repositories of real world usage profiles and use cases, and statistical models of normal and abnormal usage, as shared assets across the supply chain.
Evaluation of impact of software ageing and reliability	Develop models and testing methods for software ageing. Methodology (based on AI) for monitoring the effect of software changes on the reliability and resilience of CPS. Modelling the ageing of connected autonomous systems.

3.1.1. How do we introduce new technologies with old systems?

The evolution of most systems is incremental, and technological changes are commonly brought about by adoption and integration of new technologies onto a legacy system. Introducing new technologies onto a new system could bring significant new risks, sometimes hard to predict. Illustrating this with examples from the workshop, while connectivity (wi-fi, NFC, Bluetooth) was proven technology, its adoption in the car industry has brought about security and safety concerns relating to systems hacking, which were not necessarily common to other applications. If a product becomes hackable through the introduction of a new technology, this is not just a safety concern, but in principle the product might automatically become un-homologated. In a broader sense, the adoption of IoT with extensive / advanced sensor technology and the associated software, while it brings significant opportunities for functional innovation, it drives and increase in complexity of the system, and therefore requires significant engineering effort for the robust verification and validation of the system against the whole set of functional requirements. Systematic understanding and modelling of the interactions between the legacy system, the new system and the broader context of the SoS across multiple levels, functions and behaviours, and including human factors, is critical for the assurance of reliability.

The sustainability aspects, in particular relating to the resilience of the system throughout the lifecycle, are important consideration. Updates to the system, either at the design stage or though the life cycle alter the architecture of the system (by changing linkages through interfaces), which not only introduce risk of vulnerabilities, but also increase the structural complexity, thus reducing the flexibility and adaptability of the system. The modelling and management of margins was discussed as an illustrative example in this context. While margins are considered and defined at the design stage, successive systems updates impact on the margins, which affects the sensitivity of the system to failure modes. Thus, the reliability and resilience potential of a system is likely to be affected by updates to the system, and therefore need to be modelled as age dependent concepts. The ever-increasing multi-disciplinarity of systems is a major challenge for managing reliability assurance both from a modelling point of view (integrating multi-physics-of-failure reliability models with communication and software failure risks), and from a project management and teams interactions and dynamics point of view.

Companies also have to manage increasingly complex product lifecycles, and still have regulatory responsibility for the end of life, and extending into the next life if substantive parts of the system are continuing to be used in the next generation (as is the case with complex assets). A product lifecycle management challenge is to "innovate with obsolescence". While the concept of durability is normally defined in the context of physical systems, there is an apparent need to define durability within a complex SoS context, to support obsolescence management in the product portfolio development. Identifying the optimal "tipping point" to displace old technology is an important decision, which is fundamentally underpinned by the combination of business models and reliability/durability models. Managing obsolescence is indeed complex because it covers both legacy systems and the newer IoT technology, which has a much shorter lifespan compared to physical systems.

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3.1.2. Reliability challenges with the adoption of new materials, processes, technologies

The engineering efforts towards light-weighting in an effort to increase energy sustainability has seen the accelerated development and introduction of a wide range of applications based on new materials and composites involving new materials. There have been also significant developments in manufacturing processes – e.g. for joining different materials, adoption of 3D printing technologies for components, as well as circular economy driven technologies for recycling and reuse.

The accelerated pace of introduction of new materials has not allowed for the systematic development of knowledge about the behaviour of these new materials in terms of failure mechanisms and degradation when they are exposed to a complex range of user and environmental conditions and scenarios within the overall system. The current knowledge (including standards) about design and validation of the systems does not extrapolate to the new materials and processes, and the standard R&D for the new materials and processes does not commonly consider the whole range of usage noise and scenarios associated with practical applications.

The scalability of reliability attributes from concept testing in the lab to real world usage, with acceptable performance is more often than not a long and difficult journey. Therefore, developing new / innovative methods for modelling, testing and qualification of new materials and processes is a key priority. Opportunities for using AI to leverage existing knowledge and physics based modelling for earlier prediction of real world behaviour and risks (for example similar to methods used in other industries - such as cosmetics) has been suggested as a potential research avenue.

The shift towards electrification across the transportation sectors has also brought challenges with the reliability evaluation of both power electronics / mechatronics and embedded systems. While significant progress has been made with the reliability of high power mechatronic systems (El-Hami et al., 2018), many mechatronic systems (including off-the shelf components) adopted in particular in conjunction with the drive for autonomy, have yet untested behaviour for the new commercial application domain.

While from an OEM perspective there is a need to accelerate the introduction of innovation, methodological developments are needed to support a rigorous risk assessment associated with new materials and technology introduction in conjunction with relevant application knowledge.

3.1.3. Systematic consideration of real world uncertainty

With products and systems increasingly designed and marketed to global use, there is a significant challenge and need to systematically acquire / capture uncertainties in real uses, covering both the user demand / behaviour and the environmental factors. Understanding and characterising usage in the real world is a particular challenge for reliability validation of new technologies and systems - such as Battery Electric Vehicles (BEV). Many of the earlier assumptions on BEVs have been proven either wrong or incomplete, and the impact of the combined effect of driving styles and environmental factors on real world reliability performance is still at an early stage. While the impact of uncertainty on autonomous driving was also raised, the workshop participants have emphasized the immediate need for action on data collection and real world usage uncertainty modelling for the development and qualification of the technologies currently considered for introduction in products / market. There is also a need for standards to evolve for the testing and validation of new technologies under real world usage.

Participants have also highlighted that real world usage profiles often include niche applications with combinations of demands and environmental conditions that differ significantly from the distribution that represents the perceived normal use. Creating and maintaining / updating comprehensive repositories of real world use cases with validated statistical models has started to become feasible with the use of real-world usage monitoring systems (including data-over-the-air, DoTA). The participants recognised that collaboration across the supply chain could bring significant acceleration to the development of such repositories, which could become shared assets.

3.1.4. Impact of software ageing and reliability

As systems are becoming increasingly dependent on software, the reliability of the software systems and components needs to be rigorously evaluated. The practical challenge, articulated by the workshop participants: "*As software ages / evolves in the deployed system, how do we maintain traceability and reliability as the system is maintained under exposure to a wide range of noise factors including human /*

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user behaviour?" The discussions focussed on the distinction between (i) the ageing of software; and (ii) the impact of software changes to the whole system. The ageing process of software is driven by the updates and patches, which aim to improve functionality. In time, this leads to increased complexity of the software, which has associated increased risk of robustness failures. There are currently no methods available to industry practice to "age" software, as a part of the system reliability validation programme.

Software updates within a complex cyber-physical system often lead to emergent behaviour. Therefore, development of methods to monitor and evaluate the impact of software updates on systems reliability and safety, also considering the interaction with human factors, and throughout the system lifecycle was highlighted as a gap and research direction / priority. A compounding factor of concern in this context is the pervasive reliance on "black-box" (BB) AI software systems. The lack of "explainability" and evaluation of robustness for BB systems is of particular concern, often linked with emergent behaviour.

The ageing of connected systems and the implied requirements for software reliability was also discussed. While the work on safety and dependability of software systems for autonomous features has delivered significant advancement, there is concern around the long-term reliability performance of such systems, in the face of both internal changes (though updates and obsolescence management) and environmental pressures, including changes in regulations and validation standards.

3.2. Right first time through design

Table 2 summarizes the key points from the RT discussions, with a more detailed outline present below.

Table 2. Right first time through design - summary of challenges and research directions

Industry challenges	Research directions
Methods for risk assessment in early design	Develop model-based methods and tools ecosystem for early reliability evaluation integrated with the MBSE development. AI to support model-based reliability methods (e.g. AI based FMEA)
Robustness by design	Develop a comprehensive approach to integrated robustness focussed test cases generation for multi-disciplinary systems. Efficient testing for safety conformance with low probability of failure.
Efficient design verification	Develop a reliability growth model to integrate virtual and physical DV testing. Explore AI & agile methodologies to optimise efficiency and confidence.
Systems reliability modelling	Develop capability to expand the use of X-in-the-Loop simulation for reliability modelling and evaluation / prediction.
Documentation and sharing of knowledge	Develop and share reliability repositories with test data, conditions and models to improve prediction capability at design stage.
Reliability project management skills	Systems reliability modelling skills need to be consistently deployed - covering both systems analysis and statistical and big data / analytics driven modelling.

3.2.1. Methods for risk assessment in early design

The need for methods, tools and skills to support analysis of reliability risks early in the design was discussed across the RTs. Industry requires methods for early vulnerability assessment of a new design concept such that time and effort is not spent on concepts that are not viable. This is for both physical (new materials or technology concepts) and software driven features (e.g. ADAS features). A good early evaluation of design risks will also support appropriate estimation of costs and allocation of resources - both engineering and testing. While team based reliability methods like FMEA and FTA are well known, they are not used effectively early in the design process. A greater emphasis and methods / tools support for function analysis and function failure analysis is needed earlier in the design process, and integrated with other model based systems engineering (MBSE) approaches. A key challenge recognised by industry participants was the substantive engagement of all engineers with systems analysis for reliability. While MBSE tools provide the vehicle for ensuring traceability of requirements throughout the design process, the integrity of requirements, in particular the interface functional requirements between subsystems, is fundamental to ensuring robustness of the design. The extent to which AI based knowledge engineering methods can be used to automate design risk assessment (e.g. use AI to generate FMEAs for components and systems) was identified as a potential research avenue.

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3.2.2. Robustness by design

Robustness is associated with reliability as it relates to variability in the complex system behaviour in relation to the environmental factors which could lead to function failure. An issue has been identified in the fact that robustness is often considered too late in the design process - after the design is complete. While this is justified by the fact that the influence of the noise factors is easier to assess when the design is complete, a point has been made that a paradigm shift is needed to consider robustness a lot earlier - from the concept stage, and ensure that "*we measure what is right rather then what is easy*" from the early design evaluations. The systematic capture of noise factors and interface models (as pathways for noise to penetrate through the system) is necessary in order to accelerate the journey of innovation from lab to trusted for the real world usage. It was also discussed that with the rapid introduction of new autonomous user centred features, for many mechatronic and electronic systems (including sensors) there is insufficient robustness test data to enable appropriate evaluation and qualification. This becomes a critical issue with OTS components increasingly used in automotive applications, qualified for other applications, but their robustness for use in an automotive environment cannot be fully demonstrated due to lack of test data. This could significantly impact systems with increased levels of autonomy, and therefore methods to support faster robustness evaluation in product development are needed.

3.2.3. Efficient design verification (DV)

Deriving an optimal level of testing in relation to the DV iron triangle of "*Cost Vs Time Vs Confidence*" is still a major challenge in industry. The use of virtual / digital design tools *in conjunction* with design reliability and robustness evaluation tools deployed early in the design process is seen as a key enabler for achieving the efficiency improvement goals, but this requires a paradigm shift in design - underpinned by effective methods, tools and skills.

Development of enhanced testing methodologies were also identified, in particular for dealing with unusual use cases (e.g. "short duration harsh cycles") exposed by increasing diverse markets. Developing accelerated test methods for an increasingly diverse and compositionally multi-disciplinary systems was also discussed. Another challenge identified is the development of efficient testing procedures to validate the functional safety conformity requirements, commonly specified in terms of very low probability of failure. Integration between verification testing at design time and online performance evaluation of systems based on sensor data was also discussed as an important direction, as such approaches are used in other fields (e.g. medical). This could also open opportunities for agile approaches to design verification testing, which could increase both efficiency and confidence.

3.2.4. Systems reliability modelling

A key topic for the discussion has been on the need to develop multi-level, multi-fidelity and multi-disciplinary modelling of systems reliability, trace-able through the design process to provide a modelling continuum from early concept selection to verification testing and qualification. Multi-physics and X-in-the-loop simulation models are increasingly used in product development across industries, however, their use for reliability assessment is very limited. The prevalent approach is still to develop and validate disciplinary models (mechanical, electrical) and use these for partial virtual validation of the system. The use of such simulation models for reliability and robustness testing - including model based multi-stress tests, was highlighted as an important gap and research direction.

3.2.5. Documentation of knowledge

Improved documentation of knowledge and better sharing of knowledge across industry sectors is an important way to advance the capability to achieve reliability and robustness by design. It has been recognised that companies across the automotive and aerospace sectors tend to be protective about their own data. However, they largely share the same supplier and customer base, so there are great potential gains by "being brave and open up to share data that is not commercially sensitive". While this is to some extent already achieved by joint / cross-industry standards and recommended practice guides, a deeper sharing of data would provide significant shared benefits for reliability-based concept analysis.

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3.2.6. Reliability project management skills

The industry participants reflected that successful management of design for reliability requires both specific technical skills as well as new project management methods and skills, with a clear focus on the importance of systematic consideration of reliability early in the project. Reliability should be everyone's concern and therefore reliability needs to become embedded in the core systems engineering design skillset. Integrated methodologies for supporting systems reliability analysis early in design, linking coherently the system functional analysis with requirements and function failure analysis, and robust design verification, exemplified by the SEED methodology (Campean et al., 2013), have proven success with deployment in an automotive context. Analytical skills to support the quantitative, data driven approach to reliability modelling and prediction, is also needed. Increasingly, the skillset required is a combination of statistical life data modelling and big data analytics to capitalise on the availability of data describing uncertainty throughout the system lifecycle.

3.3. Intelligent systems health management

Table 3 summarizes the key ideas collected from discussions, with an expanded outline presented below.

Table 3. Intelligent systems health management - challenges and research directions

Industry challenges	Research directions
Data governance for reliability and dependability	Develop a standard for reliability data and model governance across industries / application domains.
Online dynamic reliability modelling	Develop dynamic reliability models for complex systems based on data streams, providing intelligent diagnostics and prognostics for systems and components.
Digital twins for reliability	Develop DT capability to monitor, anticipate and optimally manage the health of the system - with both online (failsafe) and offline (maintenance) action.
Minimal data set for reliability	Risk based models for the contextual dynamic evaluation of the availability of an autonomous system for a given mission.

3.3.1. Data governance for reliability and dependability

Across the engineering disciplines and industrial domains represented in the workshop, given the penetration of IoT technologies, data is increasingly available from multiple sources across the system lifecycle - design and development, manufacturing, operation and retirement. This is an important asset for safety and reliability analysis, and in order to support this a strong data governance is required. In this sense, data governance should not only relate to the trace-ability of data but also its processing and storage. Data cleaning is a specific example where governance should impose standards for processing, traceability, format interoperability and storage, to provide the necessary trust in data. The FAIR (Findable, Accessible, Interoperable, Reusable) data principles (European Commission, 2016) should provide a blueprint for the inclusion of reliability data. A concern that was expressed in discussion was that data standards will likely be driven by safety considerations, with reliability being less of a priority. This will likely result in continuing challenges for reliability modelling.

3.3.2. Online dynamic reliability modelling

The participants reflected that reliability models currently in use in industry are still predominantly steady state deterministic, and there is a shortage of consistent attempts and examples of dynamic reliability modelling, or models that represent the stochastic uncertainty in real world usage. With real time sensor data becoming increasingly available (e.g. data-over the air, DOTA, increasingly available for vehicles in the field), data-driven machine learning models can be developed for online system and components diagnostics and prognostics, towards an individual prediction with contextual intelligence.

3.3.3. Digital twins for reliability

While the idea of building digital twins (DT) to monitor the performance of complex systems is relatively well established, an effective DT for reliability would require data, information and models which are different from the common DTs. The merger of simulation models with sensor data models for complex systems like a vehicle is still a fundamental challenge. From a reliability point of view, we

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are interested in monitoring in real time the actual behaviour of systems and components, which is made difficult by the limited number of sensors available and the fact that the location of the sensors is often not ideal for monitoring actual behaviour of a component. A further compounding factor is that within a complex system sensors monitor behaviour at different levels of the system hierarchy, with complex relationships to identify the dynamic state of a component. The implication is that causal relationships are not comprehensively and exactly mapped, which raises the question whether AI deployed within the DT can support learning in a transparent explainable manner. A separate issue of significance is that sensor data quality is still problematic, which further challenges the inference of actual behaviour. This provides further scope and need for machine learning and AI techniques to be deployed on sensor data fusion for online learning of behaviour, with capability for diagnostics and prognostics.

3.3.4. Minimal data set for reliability

Given the inherent epistemologic uncertainty of sensor driven perceived behaviour of a complex systems, the issue of identifying with quantifiable confidence the "minimal data set for reliability" (the "small data") is of significant importance for autonomous decision making. This is both for the robust diagnostics of physical and communication systems state (system self-awareness), and the environmental awareness, to support explainable decisions for autonomous systems availability.

4. Discussion and further work

The aim of this Reliability Research Roadmapping workshop was to collect a cross-industry view of the current and future reliability challenges associated with design, development and operation of increasingly complex systems, to inform the engineering design community of directions for impactful fundamental and applied research and skills development. The workshop has clearly achieved its intended mission: a comprehensive picture of the reliability challenges has been assembled, with associated directions for research and skills development summarised in Tables 1-3.

Figure 3 provides further analysis of the research directions towards a reliability research roadmap, with reference to both the timescale for implementation and the technology readiness levels (TRLs) from fundamental research (TRL 1-3), applied / development and demonstration for specific applications (TRL 4-6) and adoption / implementation (TRL 7-9).

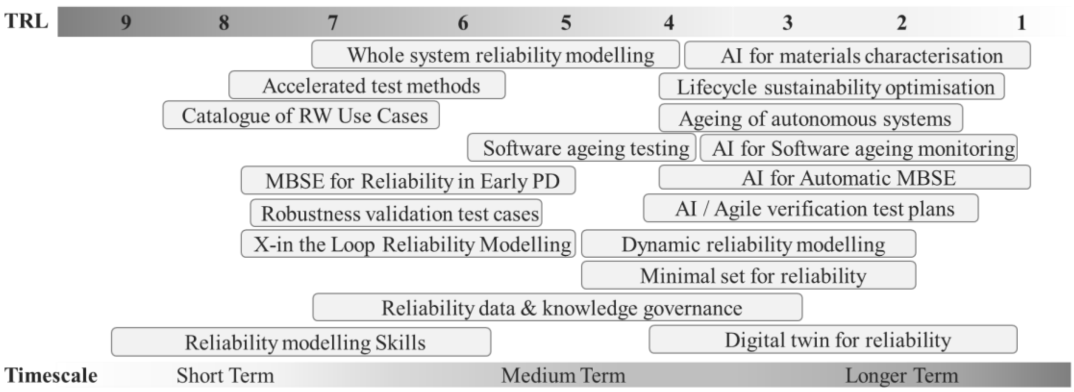

Figure 3. Reliability research roadmapping

The analysis shows that the fundamental reliability research should revolve around the deeper integration of AI in all aspects of reliability modelling - from faster proving of new materials and technologies, to smart testing and automatic systems reliability modelling at design stage integrated with usage data, and dynamic modelling of reliability under uncertainty. Modelling the ageing of autonomous systems and lifecycle systems sustainability / resilience optimisation were identified as critical areas requiring fundamental research to underpin the evolution and adoption of autonomous systems for ubiquitous commercial applications. Integration of all of the AI-based reliability modelling within a behaviour-focussed Digital Twin was seen as the underpinning for achieving the SAE JA6268 (2018) level 6 "Self-adaptive health management" of a complex autonomous system. Medium term research (TRL 4-6 - still requiring significant applied research) should centre on addressing the concerns around software ageing

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modelling and testing (including black box AI systems) and the holistic, integrated modelling of systems reliability across the physical, software and communication domains, both at design time and at run time. Medium / shorter term industrial research and knowledge transfer should focus on reliability modelling tools early in the systems design and development across the disciplinary divides, development of accelerated test methods and comprehensive robustness validation, as well as the governance of reliability and knowledge across the supply chains and industrial domains - such that data and models can be trusted and shared. Reliability modelling and project management skills are recognised as immediate priority for action across industries. This should include a good foundation in both statistics and big data analytics to complement the engineering systems analysis skills.
The reliability research roadmap provides a useful guide for academic and industry research, and the workshop has created a community driven by the common interest in advancing the methods to enhance reliability and resilience of current and future engineered systems.

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