Intelligent decision support for maintenance: A new role for audit trails

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Abstract The changing nature of manufacturing, in recent years, is evident in industries willingness to adopt network connected intelligent machines in their factory development plans. While advances in sensors and sensor fusion techniques have been significant in recent years, the possibilities brought by Internet of Things create new challenges in the scale of data and its analysis. The development of audit trail style practice for the collection of data and the provision of comprehensive framework for its processing, analysis and use should be an important goal in addressing the new data analytics challenges for maintenance created by internet connected devices. This paper proposes that further research should be conducted into audit trail collection of maintenance data and the provision of a comprehensive framework for its processing analysis and use. The concept of 'Human in the loop' is also reinforced with the use of audit trails, allowing streamlined access to decision making and providing the ability to mine decisions.

1 Introduction

Increasingly manufacturing industry is adopting network connected intelligent machines in their factory development plans. This movement to incorporate new technology incorporating advances in Artificial Intelligence is described and encouraged by a number of international government/industry initiatives. The Industry 4.0 movement is one such initiative, between the German government and national industries, with a role to envisage and promote the use of new technologies and organizational methods for manufacturing (German Federal Government, 2016). Cyber Physical Systems (CPS) are a core theme of Industry 4.0 encompassing the further integration between machines and computing resources. According to Lee

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and Bagheri (2015) CPS as the integration of physical assets with intelligent software systems that will enable a new generation of maintenance practice. In addition, the enhanced information processing and analysis opportunities provided by the ubiquity of sensor use in modern machinery to provide data streams and resulting Big Data sets is seen to create potential for new products and new types of manufacturing models. A key challenge for maintenance practice is how the opportunities brought by this expansion of data can be best realised. The issue of data provenance is key in the formation of meaningful analytics and, when coupled with an audit trail framework, offers a valuable methodology for reliable and secure data driven decision making in the implementation of maintenance practice.

2. Literature review

The quality and provenance of data are important factors when engaging in any form of analytics. Lin et al. (2007) conducted a survey into data quality relating to asset management information. The survey found that processes and software for asset related data quality management were missing in a majority of organisations interviewed; in addition organisations did not have a strategy in place regarding data quality (Lin et al., 2007). Haider (2015) propose a framework for asset lifecycle management data governance, stating that organisations need policies to ensure data quality is inherent in their operation. Woodall et al. (2015) define seven information quality dimensions for organisations to audit their operations by to establish an actual level of data quality and potentially identify areas for further improvement. The OPC UA (OPC Unified Architecture) standard for industrial system inter-communication while comprehensive in its specification can be complex and expensive for an organisation to implement. The work of Henßen and Schleipen (2014) examines the role that the AutomationML mark-up language can play in simplifying the use of OPC UA models with existing data sets and streams expressed in XML. According to Henßen and Schleipen (2014) use of OPC UA directly is a complex task, utilising AutomationML mapping to OPC UA opens up the opportunity of streamlined connectivity with OPC UA compliant systems and manufacturing systems. Liyanage et al. (2009) detail the semantic web, ontology and use of XML metadata description use for information exchange in e-maintenance. Karray et al. (2009) make the point that semantic interoperability between systems is key to the successful operation of e-maintenance. Grangel-Gonzalez et al. (2016) take the semantic communication notion a step further by producing a metadata software shell for Industry 4.0 components. The approach is based on RDF (Resource Description Framework) and OWL (Web Ontology Language) and aims to allow for new functionality, described by ontological elements, to be integrated into the communication framework with minimum disruption (Grangel-Gonzalez et al., 2016). In combination with machine intelligence such a framework could acts as an enabling protocol for automation efforts in maintenance activities and factory operations alike.

Vaughn et al. (2005) examine the possibility for automated cyber vulnerability recognition where sensor data is used to trigger security warnings. The aim of automated cyber security is also sought by Abreu et al. (2015) with the use of audit trail data. With this work Abreu et al. (2015) employ machine learning techniques to derive patterns and insights to, in principle, enable automated actions and decisions to be made. Duncan and Whittington (2016) advise on the regular analysis of audit trails in the effective securing of cloud based systems. While useful in countering intrusions into maintenance systems it is also the case that such approaches provide much of the rigor and data management practise required to ensure quality and enforce standards within an organisation and its supply chain and linked parties. The use of such audit trail techniques in manufacturing has been much less evident though its use with IoT has in outline been explored by Lomotey et al. (2018) in research exploring the need for visualisation of internet connected devices. In addition Lomotey et al. (2018) propose a provenance methodology to allow for improved traceability and identification of routes through a network that specific data points may take. Efforts towards a unified metadata syntax and model for provenance are embodied in the work of Moreau et al. (2011) who put forward the Open Provenance Model (OPM), enabling the unified and secure exchange of such data between networked systems and entities.

3. Maintenance and Retaining 'Humans in the loop'

With the use of such audit trail based intelligent data mining there arises the potential need to explain the reasoning behind automated decisions to humans for the purposes of evaluating/ensuring provenance of maintenance data. Duncan and Whittington (2016) make a number of recommendations on how the audit trail for cloud computing could be improved; the following are an adaptation of a subset of those recommendations with relevance to the maintenance field:

- A strict regime of data log migration to data storage is required
- Further understanding on information flow within manufacturing is required
- Enhanced data security is required to safeguard collected audit trail data and digital entry points to manufacturing systems from cyber attackers

It is the case that a 'human in the loop' is required as their expert knowledge and overview capability can be leveraged, in particular, to help ensure data and processes security. A vital step along the road to automation is the inclusion of human expertise along with standards such as the MIMOSA open system architectures for CBM and EAI (Enterprise Application Integration) (MIMOSA, 2017), which potentially provide a wider underlying structure for the concept of maintenance audit trails. Furthermore, "human in the loop" – generated events can be viewed as a crowdsourced timeline of maintenance linked knowledge, contributing to maintenance and asset management data quality, if adequately mined (Pistofidis et al. (2016).

4. The Audit Trail for maintenance

When considering the implementation of audit trail practice within an industrial setting it is important to consider the data flows currently available. Many enterprise systems in organisations, such as ERP (Enterprise Resource Planning), possess event logging capabilities. Such event logs may be mined in order to reconstruct a chain of activities that have taken place within the organisation and administrated by the system (Turner et al. 2012). Events, even when not mined as complete process chains, may still be further augmented by semantic descriptions (attached as metadata tags) to establish provenance. Sensors in both production machines and located within the production line / maintenance environment can provide a wealth of data when systematically connected to data repositories. This data may even be available in the form of a continuous stream, informing of the live status of the asset in question. Real time or near to real time evaluation of machine condition data can provide a new level of insight when combined with prognostic techniques within maintenance decision support and planning systems. Use has been made of audit type data in industrial applications.

A sensor fusion approach has been used by Payan et al (2016) in the development of proactive safety metrics for helicopters. In this research Payan et al. (2016) fuse the outputs of flight data monitoring to form the basis for predictive safety measures, with the potential to advise preventative measures. Such an approach may also inform the development of audit trail compilation and use to enhance the scheduling and performance of maintenance activities. One way of presenting data provenance information in a non-technical fashion is through the provision of a text based audit trail (written in plain language) describing the individual steps taken to arrive at a generated recommendation (including any calculated weightings or percentages used). In addition the user should be made aware of the sources of data used in the generation of decisions and a suitable provenance should be available for each individual source for human based cross checking and evaluation. The concept of 'Human in the loop' is reinforced within this framework through streamlined access to decision making and the ability to mine audit trails of decisions (and the reasoning behind decisions) and activities that have occurred within the Internet connected production line. There will be a necessity to capture and store data streams from the production line and audit trails of decision making within the semantic sandwich layer and monitored activities within the system. A big data repository will be required along with connectivity to other data stores and streams within the organisation.

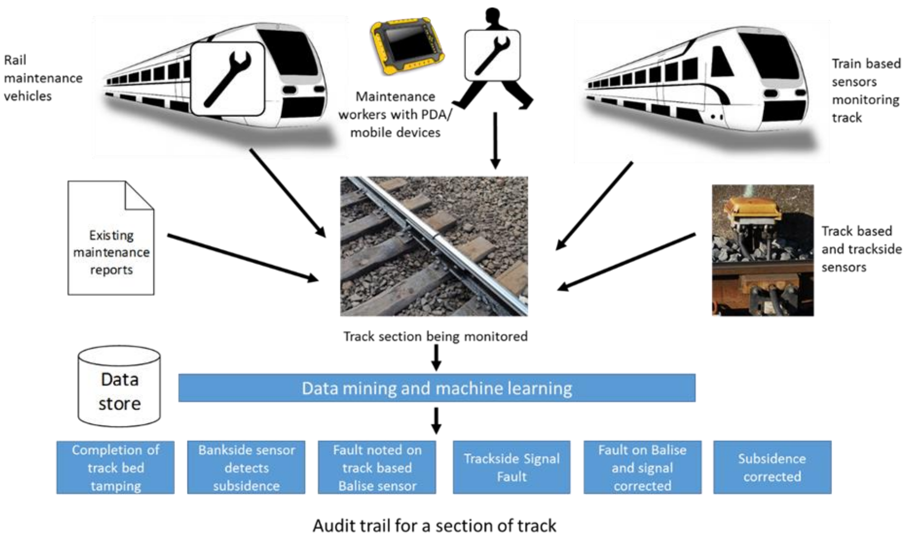

Figure 1: An audit trail drawn from rail maintenance activities and sensor streams for a section of track

Figure 1 illustrates the concept of the audit trail with an example drawn from railway maintenance activities. In Figure 1 it can be seen that for a section of track there are a range of maintenance activities that may involve: maintenance workers, feeding back reports via mobile devices; rail maintenance vehicles with sensors; passenger trains fitted with track and infrastructure monitoring sensors. In addition a number of trackside sensors may also stream back data to a control centre concerning a range of environment specific parameters. The scenario depicted in Figure 1 relates to the possibility that sensors have registered faults with a Balise (track based transponder forming part of an Automatic Train Protection (ATP) system) and trackside signals in a period of time after the section of track has been tamped (where the ballast bed of the track is adjusted). In addition a bankside sensor has noted some occasional subsidence in the past. All these data streams are recorded at a central control centre. The use of data mining may establish a causal link between these events taking into account the outlier measurement from the bankside sensor leading to the root cause of the fault.

New forms of data capture are proposed for use in the rail industry that include RFID for the location of trains, lower cost (and more compact) condition monitoring sensors built into train components, and sensors on trains monitoring the track and overhead power lines (Kans et al., 2015); in essence the use of IoT for data point and stream collection is proposed allowing physical assets to communicate their real time status and health. Kans et al. (2015) outline an intelligent maintenance approach capable of interaction with Rail Traffic Management systems for the dynamic mitigation and rerouting of services on identification of infrastructure and or rolling stock breakdowns. A focus within the work of Kans et al. (2015) is the use of forecasting and prediction of faults through range of techniques including machine learning. Decision making within intelligent maintenance systems can be complex due to the sheer variety of data sources. Through the use of metadata descriptions and timestamps it is possible to establish a process for the analysis of collected data. The audit trail establishes the order of events via timestamps and the output from data mining/machine learning. The metadata descriptions can be used to describe the data collected and its potential use (along with numerical values) and combined with event logs generated by ERP systems; such descriptions can be used within the data analysis process and the text displayed in the form of an annotated process to human operators and managers (and potentially track side workers). Such audit trails can help reveal the path of the automated decision making within an intelligent system. Vergidis et al. (2015) propose the use of an annotated process to describe the intelligent optimised composition of web services; an extension of such a technique could be employed to compose metadata trails within analysed data through text extraction and the additional use of semantics, context based computing and machine learning based data mining approaches.

5. Discussion

It is clear that initiatives such as Industry 4.0 are changing attitudes towards digital connectivity and automation in manufacturing, though it is the case that there is a need for a holistic understanding of data being collected and analysed. It is also true that industry is still missing an overall framework for digital maintenance. Advances in sensors and senor fusion techniques have run-ahead of suitable processes and systems capable of fully harnessing their outputs. The quality and provenance of data are important factors in data management. With maintenance rapidly adopting key Industry 4.0 technologies, such issues attain increased importance in the delivery of successful applications and services. Product and asset lifecycle data are increasingly acknowledged as valuable assets (Kubler et al., 2015). Therefore their own lifecycle needs to be appropriately managed and this could become a key factor in establishing a credible audit trail for maintenance activities and data. Imran et al.

(2017) provide the following outline points to take account of when collecting and describing the provenance (perhaps through metadata tagging) of data products:

- From where a data product was acquired?
- By whom and when the data product was created?
- Who are the authorized stakeholders of the concerned data product?
- In what transformations and computations has it been used?
- What were the inputs for the generated output data item?
- Which criteria were applied in the creation of the data product?

Work in the area of event logging based audit trails that have been utilised in the field of cyber threat detection within networked software systems, are of direct complimentary use in ensuring that data flows are not compromised by intruders. The implementation of audit trail methodology could therefore bring inherent additional security benefits to any implementing organisation.

Conclusion

Further work remains to be completed on understanding information flows within manufacturing and how digitisation of systems and information will impact maintenance activities. Though it is put by the authors that clear processes to support audit trail style collection of maintenance data and the provision of a comprehensive framework for its processing, analysis and use should be important goals for the research that must be completed in the near future for full enablement of digital maintenance practice. The concept of 'Human in the loop' is also reinforced with the use of audit trails, allowing streamlined access to decision making and the ability to mine decisions (and the reasoning behind decisions for machine assisted workers and managers). Security concerns inherent in the connection of live production line assets to networked systems may well be allayed by the introduction of an audit trail methodology. Developments in the security arena and their use of audit trail must also be acknowledged in future research relating this practice to maintenance activities. The ability to provide procedural structure to data for reuse and communication within an Industry 4.0 maintenance system will be vital for any future move towards semi or fully autonomous maintenance activities.

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