Towards an Open-standards based Framework for achieving Condition-based Predictive Maintenance

Karamjit Kaur, Matt Selway, Georg Grossmann, Markus Stumptner
School of ITMS,
University of South Australia
firstname.lastname@unisa.edu.au

Alan Johnston
MIMOSA
atjohn@mimosa.org

ABSTRACT

The advent of Industrial Internet of Things (IIoT) technology has significantly optimized the industrial operations management by connecting industrial assets with information systems and, hence, with business processes. The IIoT forms the backbone for materializing the Industry 4.0 initiative. Actionable insights obtained from industrial analytics are one of the pivotal means for achieving intelligent operations and maintenance. Intelligence refers to making optimal decisions for both automated and human-in-the-loop decision making. Condition-based predictive maintenance (CBPdM), also known as Maintenance 4.0, is among the major focus points of the Industry 4.0 and IIoT. In this paper, we discuss the existing standards related to condition-based maintenance and the potential of the Open Industrial Interoperability Ecosystem (OIIE), a MIMOSA led initiative, as a framework which extends previous open standards for achieving CBPdM. We illustrate how the framework addresses the requirements of Industry 4.0 and CBPdM.

ACM Classification Keywords

B.4.3 Input/Output and data communications: Interconnections (Subsystems); I.2.1 Application and Expert Systems: Industrial Automation

Author Keywords

Condition-based predictive maintenance; Maintenance 4.0; Industrie 4.0; IIoT; OIIE Framework; OSA-CBM; OSA-EAI

INTRODUCTION

Implementation of Industry 4.0 is driven by the recent advances in cyber-physical systems, cloud computing, big data and industrial wireless networks [41]. Built on this connectivity, large amounts of data emanating from connected sensors are aggregated and analyzed to provide actionable insights and ability to generate automated decisions. The real-time data access and derived intelligence is driven by the ongoing, recurring flow of information and actions between the physical and digital worlds also known as the "physical-to-digital-to-physical loop" [33]. Data from physical assets is digitalized and analyzed to generate insights which result in real-world physical actions. This loop allows harnessing of data and a pro-active approach to determine future maintenance needs and their urgency.

The Internet of Things is increasingly being adopted by manufacturers to simulate their production processes, remotely control machines and monitor their operations. Linked resources send rich data through the IIoT which can be used to improve collaboration between performance, operations, and asset maintenance. Maintenance is one of the prominent operations with major impact on business performance [30]. IIoT uses sensors and connected devices across the industry to make smart maintenance decisions based on real-time accurate data which detects even slight deviations from the benchmark key performance indicators (KPIs) [9]. A large number of companies are combining the capabilities of IIoT and Big Data to predict equipment maluncțions. The accuracy of forecast is further getting more precise with improved Artificial Intelligence (AI) techniques and machine learning tools.

Failure-driven maintenance is a reactive maintenance approach which is carried out only after the occurrence of a malfunction, or breakdown of equipment [4]. Time-based maintenance (a.k.a. periodic preventive maintenance) is based on either mean time between functional failures (MTBF) or machine usage [7]. Instead of running a part until failure (failure-driven maintenance), or replacing a good part which may have life left (time-based maintenance), ***condition-based predictive maintenance*** (CBPdM) performs repairs only when needed or just before.

Recently, organisations have adopted CBPdM where maintenance is carried out according to the need indicated by the equipment condition, enabling maintenance managers to better predict a possible breakdown event based on current and historical data [24]. This proactive approach is more data-driven and analytical in nature as compared to the previous approaches. Benefits associated with CBPdM are fewer equipment downtime, fewer urgent work-order requests, lower maintenance costs, enhanced asset performance, considerably improved asset reliability, overall enrichment of the business performance and better budget planning. A detailed comparison of CBPdM with time-based maintenance and its benefits over the latter

based on practical factors is provided in [10]. Limitations of time-based maintenance methods of equipment and the advantages of predictive maintenance techniques in anticipating the onset of equipment failure is discussed in [16]. An overview of the preventive and condition-based maintenance techniques with emphasis on how these techniques achieve maintenance decision making is provided in [1]. The authors concluded that CBPdM is more realistic based on the fact that 99% of equipment failures are preceded by indications about occurrence of failure.

CBPdM is among the major focus points of the Industry 4.0 and IIoT initiatives [32] and is also popularly known as Maintenance 4.0 mainly because of its applicability to Industry 4.0 [18]. Maintenance 4.0 forms a subset of smart manufacturing systems which are autonomous in their operation, capable of predicting failures and triggering maintenance activities. These systems are comprised of smart equipment in form of embedded or cyber-physical systems forming the digital twin of physical assets. To achieve near zero defects, near zero down time and automated decision making based on condition monitoring, world class diagnostics and prognostics need to be implemented [25]. Prognostics parameters indicate potential problems which can lead a device to deviate from its acceptable performance level. Specific parameters such as valve stiction and pump vibrations are monitored using sensors, whose data is collected over time to establish a trend.

The most advanced form of maintenance is *prescriptive maintenance* which builds on CBPdM as it provides further guidance on the maintenance task as well as provide diagnostics [21]. Prescriptive maintenance strategies extensively use advanced data processing and visualization techniques such as graph analysis, simulations, neural networks, complex event processing, heuristics and machine learning. These tools provide the capability to calculate the timing and effect of failure, thus, determining the priority and urgency of the maintenance activity. In addition, these techniques supplements prescription of guidance for the repair activity. For example, providing a predefined Solution Package[1], or a pre-planned work order along with the request for work to be sent to the maintenance management system. Both CBPdM and prescriptive maintenance are based on the use of IIoT concepts.

The industry is moving forward at a fast pace to reap the benefits of the Industry 4.0 revolution, but unfortunately standards bodies have not been able to keep up with this pace. Standards form the basis for introducing new technologies and innovations, ensuring that the products, components and services supplied by different companies are mutually compatible. Open standards are publicly available standards which are easy to adopt and improve upon. Even after the wider adoption of CBPdM in industry, to the best of our knowledge there does not exist any standard framework or reference architecture for it. This paper contributes by describing the existing open standards related to condition-based maintenance and how the research/industrial community has benefitted from them. Furthermore, we discuss the potential of Open Industrial Interoperability Ecosystem (OIIE), a MIMOSA led initiative, as a framework for achieving CBPdM. We illustrate how the framework addresses the requirements of Industry 4.0 and CBPdM. MIMOSA has a history of developing and publishing open systems architecture for condition-based maintenance (CBM) and enterprise application integration (EAI). The OIIE framework for CBPdM is built upon these well-adopted open-standards and extends them to utilize the potential offered by IIoT and Industry 4.0.

[1] http://www.mimosa.org/oiie-use-case-7

INTERNATIONAL STANDARDS FOR CBM

In this section, we discuss various standards related to CBM and how MIMOSA is coalescing with them. Table 1 lists various standards related to the CBM approach. Due to space constraints, we will only discuss the OSA-CBM and OSA-EAI standards and how they have either implemented open standards such as ISO-13374 or can complement open standards like IEEE-1451. The Open System Architecture for Condition-Based Maintenance (OSA-CBM) specification is an open standards based architecture which acts as a reference point for implementing condition-based maintenance systems. It was developed in 2001 by an industry led team partially funded by the US Navy through the DUST program [39]. The participants ranged from industrial, commercial, to military applications of CBM technology: Boeing, Caterpillar, Rockwell Automation, Rockwell Science Center, Newport News Shipbuilding, and Oceana Sensor Technologies. Applied Research Laboratory of Penn State University and MIMOSA were the other prominent contributors. It is now managed by the MIMOSA[2] standards body and its version 3.1 was publicly released on August 1, 2006.

OSA-CBM is a robust non-proprietary standard which added details of data structures and interface methods for implementing the six blocks of functionality in a condition monitoring system defined by the ISO-13374 standard (Condition Monitory and Diagnostics of Machines). OSA-CBM has become the de-facto standard for CBM, encompassing the complete range of functions from data collection through to the recommendation of specific maintenance actions. U.S. Army and Navy have evaluated the OSA-CBM architecture as a part of their global maintenance infrastructure [34, 31]. According to [2], MIMOSA OSA-CBM is the most evolved CBM related standard.

OSA-CBM can be complemented when used in conjunction with the IEEE 1451 smart transducer interface standard which is an open standard for distributed measurement and control. IEEE 1451 handles the integration of network sensors, while OSA-CBM handles the integration of software components responsible for condition monitoring [26]. Researchers have implemented a distributed embedded condition monitoring systems based on OSA-CBM standard, which offers reusable software for a class of condition monitoring applications [36]. Their open software framework was developed using Java and RMI middle-ware, whose application is validated on a distributed gearbox condition monitoring system.

[2] http://www.mimosa.org/

Standards	Description
IEEE 1451	Smart transducer interface for sensors and actuators
IEEE 1232	Artificial Intelligence Exchange and Service Tie to All Test Environment
ISO 13372	Condition monitoring and diagnostics of machines - Vocabulary
ISO 13373-1	Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 1. General procedures
ISO 13373-2	Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 2. Processing, analysis and presentation of vibration data
ISO 13374	MIMOSA OSA-CBM formats and methods for communicating, presenting and displaying relevant information and data
ISO 13380	Condition monitoring and diagnostics of machines - General guidelines on using performance parameters
ISO 13381-1	Condition monitoring and diagnostics of machines - Prognostics, general guidelines
ISO 14224	Petroleum, petrochemical and natural gas industries - collection and exchange of reliability and maintenance data for equipment
ISO 17359	Condition monitoring and diagnostics of machines - General guidelines
ISO 18435	MIMOSA OSA-EAI diagnostic and maintenance applications integration
ISO 55000	Asset management

Table 1. International standards related to CBM

The Open Systems Architecture for Enterprise Application Integration (OSA-EAI)[3] is another standard developed and managed by MIMOSA which defines data structures for storing and progressing information about all characteristics of equipment into enterprise applications. It focuses on information integration of asset life-cycle management (ALM) applications using a common standardized maintenance database, which is one level above the condition monitoring (CM) systems. OSA-CBM data can be directly mapped into any OSA-EAI-compliant relational database maintenance systems with ease, allowing better integration of CM and ALM systems. Examples of OSA-EAI compliant commercial off-the-shelf (COTS) software are Emerson Process Management RBMWare, Rockwell Emonitor Odyssey and IBM Maximo Oil and Gas.

OpenO&M[4] is another MIMOSA led initiative for collaborating multiple industry standards organization to harmonise the standards used for application integration in operations and maintenance. Multiple industry-focused JWGs exists under this initiative. Until now, the OpenO&M technical committee has produced two specifications for connecting information systems in the manufacturing domain, the OpenO&M Information Service Bus Model (ISBM) and Common Interoperability Registry (CIR) which are explained in Section 3.

MIMOSA is also working along with OPC foundation in a JWG to develop an OPC UA Information Model for MIMOSA CCOM[5] in which OPC UA brings information from the factory floor and MIMOSA play its role in Asset Management. The OPC foundation[6] creates and maintains open standards for connectivity of industrial automation devices and systems. OPC Unified Architecture (OPC UA) is a machine to machine communication protocol for industrial automation developed by the OPC Foundation. It bridges the gap between the service-oriented enterprise IT systems and the automation and control systems, including intelligent devices. It is a key standard for Industry 4.0. The prominent feature of platform independence makes communication compatible for different types of hardware and software applications [14].

The work in [40] describes design and implementation of a system which integrates enterprise asset management systems (using MIMOSA OSA-EAI and OpenO&M CIR specifications) and condition monitoring systems (using OPC UA) . OPC UA data sources interfaced with OSA-EAI web services, while the CIR server facilitated the integration by mapping OPC UA object types to keys that referred the OSA-EAI. Another group of researchers have implemented a remote monitoring solution named Wapice Remote Management (WRM) platform utilizing OPC UA, MIMOSA OSA-CBM, and OSA-EAI [35].

An extensible condition monitoring software called BUDS was implemented using OSA-CBM with focus on vibration condition monitoring in [28]. The authors further investigated the use of the MIMOSA OSA-EAI database for implementing condition monitoring systems, and also discussed the issues and challenges faced during the development process. They concluded that OSA-EAI is suitable for use as a condition monitoring database because it covers the major aspects of condition monitoring, including asset and sensor registry management, measurement event management, and storing raw and processed signals. In [11], authors report their experience of implementing the OMAHA project using OSA-CBM and OSA-EAI. OMAHA project builds a demonstrator of physical health management for a fleet of passenger aircraft and implements a simple builder API for binary OSA-CBM messages.

A software framework for prognostic health monitoring of ocean-based power generation using MIMOSA CBM and EAI web services on vibration data is implemented in [5]. In [12], authors have provided an adaption of OSA-CBM architecture for providing Human-Computer Interaction through mixed interfaces. They have also proposed a methodology for management and visualization of information using mixed reality for interaction with OSA-CBM modules. In addition to the above, many researchers have adopted or extended OSA-CBM and OSA-EAI in their implementations which demonstrates the wider adoption of these open standards [38, 23, 6, 8, 22, 13, 20, 37].

Motivated by the success and popularity of previously published open standards, MIMOSA aims to extend CBM use-cases and scenarios to ensure support for (I)IoT devices and predictive maintenance. Interoperability of the asset management systems is crucial in achieving accurate diagnosis and prognosis as it can highly augment the data received from assets. There does not exist any coherent standards-based architecture for achieving interoperability among various components of an enterprise business system, required to achieve CBPdM. With the OIIE (explained in next section), MIMOSA

[3] http://www.mimosa.org/mimosa-osa-eai
[4] http://www.mimosa.org/openom-initiative
[5] http://www.mimosa.org/mimosa-ccom
[6] https://opcfoundation.org/

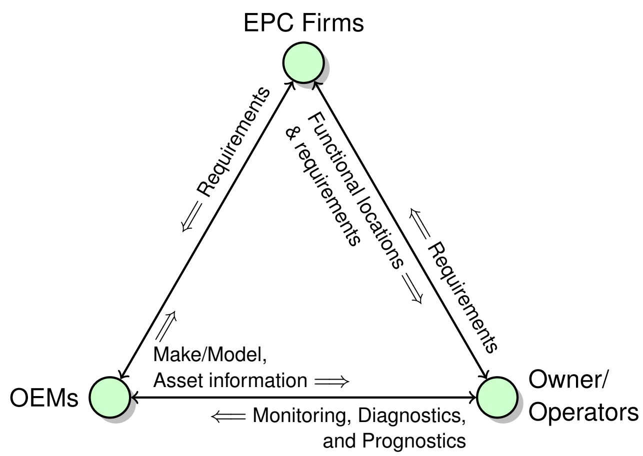

Figure 1. Connections between organisations in the Oil & Gas Domain

aims to achieve interoperability of asset lifecycle information (including design, construction, operations, maintenance, etc. information) through the adoption of open information standards across manufacturing, fleet, and facilities environments.

OPEN INDUSTRIAL INTEROPERABILITY ECOSYSTEM

The Open Industrial Interoperability Ecosystem (OIIE)[29] ties together the previously published MIMOSA standards and provides interfaces for the integration and use of relevant domain standards across the ecosystem. An OIIE *ecosystem* crosses system, software, and organisational boundaries to create a managed, distributed, federated System of Systems such as that required for the exchange of information between EPC (Engineering, Procurement, Construction), Owner/Operators, and OEM (Original Equipment Manufacturer) companies for the design, construction, operation, and maintenance of process plants in the Oil & Gas domain (refer Figure 1). The key components of the OIIE are briefly described in the following.

MIMOSA/OpenO&M ws-ISBM (Web-Service Information Service Bus Model, which defines Web Services for an Enterprise Bus that supports both inter-/intra-enterprise communication through multiple modes, including request/response and publish/subscribe. The ISBM provides the backbone upon which the OIIE operates. The original standard[7] defines a set of SOAP/XML-based web services for configuring an ISBM instance and exchanging messages across it. The ISBM supports security at the transport layer via SSL/TLS and channel authorisation through token-based security.

MIMOSA CCOM (Common Conceptual Object Model), formerly part of the OSA-EAI [27], is the primary means of exchanging asset information in an OIIE. It provides a conceptual model and XML Schema for asset lifecycle data, including: design (functional locations, requirements, etc.), serialised assets (built/installed assets, models, and their properties), CBM (measurements, signals, alarms, etc.), and work management (work orders, plans, etc.). It leverages other standards such as the UN/CEFACT Core Component Types and OAGIS Platform Specification. In particular, messages exchanges are performed primarily in the form of the OAGIS Business Object Document (BOD) format[8], which provides a standardised message format comprising message metadata, the verb or action to be performed, and a noun or object to perform the action on. CCOM 4 defines BODs for general querying as well as BODs developed to address the use-cases defined for the OIIE.

Management and administration is an important aspect of an OIIE. As more and more systems/devices are connected, the complexity of the ecosystem grows and it has been recognised that the ability to configure, manage, and govern the ecosystem as a whole is required. Such management becomes the responsibility of the *Ecosystem Administrator* and helps to ensure data integrity and compliance. There are several components that assist the administration of the ecosystem:

1. The SDAIR (or Structured Digital Asset Interoperability Register) specification defines the functionality required for the management of Master Data available to applications in the OIIE for asset lifecycle and facilities management. Chiefly, it enables the registration of unique identifiers (UUID) for entities to be used consistently in CCOM exchanges across the OIIE; management of Systems of Record, which ensure data is modifiable only by the system that has the right to do so; supports Management of Change to ensure that a full audit log is available for asset configuration changes published by applications in the OIIE; and facilitates the mapping of property sets to an organisation's internal definitions. An SDAIR is typically provisioned with data during Engineering handover and Operations and Maintenance Provisioning.

2. The OpenO&M ws-CIR (Common Interoperability Register)[9] provides a SOAP/XML Web Service interface for the mapping and retrieval of identifiers used by different systems within an OIIE instance. Such an interface allows standardised and simple translation of identifiers, for example, between those of an internal application, standard data dictionary, or reference data library and the CCOM UUIDs used in exchanges across the OIIE.

3. The Service Directory specifies a Web Service interface that provides configuration and registration of services with the ISBM. Such centralised configuration allows the Ecosystem Administrator to specify the applications, which services they support, their scope, the exchange modality (i.e., request/response or publish/subscribe), and the associated ISBM endpoint, channel, topic configuration. Applications can then query the Service Directory to dynamically determine what channel/topic/request mechanism it should use to retrieve or publish necessary data.

Transformation is the final piece in the OIIE to support interoperability between a large number of disparate systems and devices. The transformation component can be configured as part of the OIIE just as any other system/application; however, its purpose is to transform the data it receives over the ISBM to the desired format (usually MIMOSA CCOM) and output

[7] http://www.openoandm.org/ws-isbm

[8] https://oagi.org/

[9] http://www.openoandm.org/ws-cir

the result to another channel/topic on the ISBM according to its configuration. Such an approach has been demonstrated to work in the 2012 OGI Pilot, in which the UniSA Transform Engine [3] was used to transform engineering design data from multiple vendor formats into CCOM during digital handover and provisioning of O&M systems.

Using these components, the OIIE aims to produce a truly plug-and-play environment, where vendors of COTS software can provide OIIE compliant adaptors rather than individual end-user organisations developing large numbers of point-to-point adapters.

MIMOSA has developed the OIIE around a use-case-based architecture through consultation with industry partners. The use-cases help drive the definition of scenarios and events (i.e. message exchanges) that the OIIE must be able to support (but are not necessarily required in every implementation/instance of the OIIE). This use-case-based approach allows the incremental development of standardised capability for the OIIE, demonstrated through the ongoing 'Oil & Gas Interoperability Pilot' (or OGI Pilot). Previous phases of the OGI Pilot have demonstrated the digital handover of design information from EPCs to Owner/Operator systems between differing standards[10]. An ISO Technical Specification is being worked on by ISO TC184/WG6 to provide guidelines for sharing design information between standards.

Previously defined CBM use-cases and scenarios, where work orders are triggered automatically as a result of condition monitoring, are defined at a higher-level between the "Maintenance Management System" and the "Work Management System" (in whatever form they are realised). With the OIIE, MIMOSA aims to extend CBM use-cases and scenarios to ensure support for (I)IoT devices and Predictive Maintenance.

OIIE AS AN ARCHITECTURE/FRAMEWORK FOR IIOT AND CBPDM

One of the common assumptions for IIoT (Industry 4.0) environments is that standards and interoperability are a given (e.g. [19, 41]). As the OIIE is a platform for (open) standards-based interoperability, its application to an IIoT environment is a natural fit and is a natural evolution of the original architecture [15]. The prognosis and health management (PHM) system of the OIIE framework is responsible for predicting the impending faults and to determine the remaining useful life of machinery. An efficient PHM can significantly speed up fault diagnosis by pin-pointing which parts of the machinery are most likely to fail and will need maintenance, thereby achieving CBPdM.

Figure 2 illustrates the OIIE architecture. The top of the diagram shows the different activities or systems involved in the lifecycle operations of a plant or facility. Each of these 'activities' may be a system or comprise Systems of Systems that can communicate directly with one another or through the ISBM. Moreover, the communication between systems may be intra- or inter- Enterprise. In the centre, the ISBM facilitates communication between the different components through web-services supporting both request/response and publish/subscribe modalities. While the initial specification defined SOAP/XML web-services, the ISBM specification is being revised to incorporate more lightweight RESTful/JSON web-services in an extensible fashion that will support the integration of other data formats and protocols in support of direct IIoT connections.

In the middle, the figure illustrates the myriad of connections that may occur between different components, IIoT devices, and the ecosystem as a whole (via the ISBM). It is common that the lower level automation and control networks (Layers 2 and below of the Purdue Reference Model [42]) are separated from the rest of the business network (Layers 3 and above of the Purdue Reference Model) by trusted systems. These trusted systems are often connected by local IIoT connections, field networks, or some other combination. The higher-level systems will then communicate with the rest of the OIIE via the ISBM. However, with the introduction of (I)IoT, the barriers are broken down slightly, with devices more typically preferring more direct connections to one another and higher-level systems. This is illustrated to the left of the diagram. This does not eliminate the need nor use of the OIIE, however, as it is still important to manage and govern the overall ecosystem. In that light, the OIIE can be used to manage *negotiated* access to the trusted systems for IIoT devices that exist outside of it.

The bottom of Figure 2 shows the connections to both industry-wide and enterprise specific reference data libraries (RDLs). Each of these components may comprise multiple RDLs of different origins and provide shared context for data exchanges in terms of common classes, terminology, and taxonomies. In particular, this includes metadata for IIoT devices. Another initiative of MIMOSA is the Industry Standard Data Definitions project (or ISDDs) which aims to provide a common basis for the digital capture and exchange of datasheet oriented properties typically published by standards organisations such as ISA, API, IEC, etc. The ISDD project covers the representation of property sets, their definitions, and exchange based on CCOM. This same framework can be used to represent the IIoT device metadata in RDLs as well as the definition of the data transmitted by IIoT devices. Moreover, capable IIoT devices can use such standardised definitions to exchange data directly with the OIIE.

Its core set of features addresses all of the principles of Industry 4.0 identified by Hermann et al. [17]:

Interoperability is the primary goal of the OIIE, in particular, standards-based interoperability. In the context of IIoT, this interoperability will includes a combination of device-to-OIIE, device-to-system, and device-to-device connectivity.

Virtualization relates to the need to have a 'virtual copy' or *digital twin* of the system and processes. Creating and maintaining such a digital twin is one of the driving forces behind the OIIE as it provides the context required to support systems and services such as CBPdM.

[10] http://www.mimosa.org/news/recording-live-oil-gas-interoperability-ogi-phase-1-pilot-demonstration

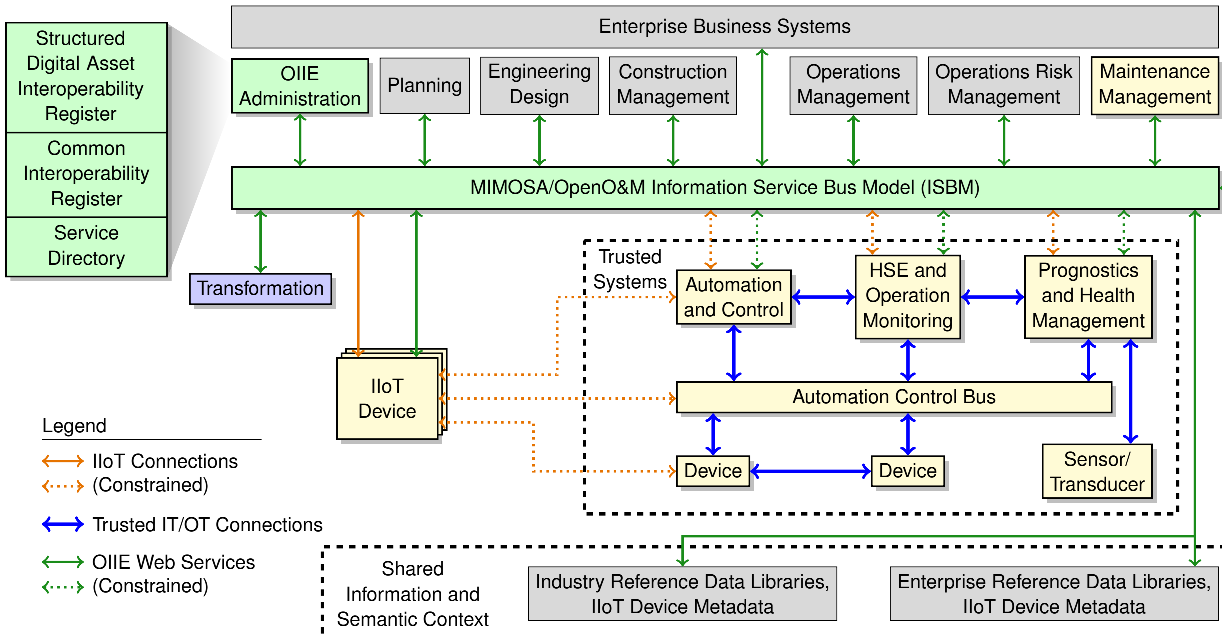

Figure 2. OIIE Architecture for IIoT. Green components indicate MIMOSA standards and specifications; yellow components highlight IIoT and Maintenance related aspects of the architecture.

Decentralization is provided as an OIIE instance comprises a System of Systems; there is no centralisation of decision making or data. The result is a federated distributed system. However, management of the whole ecosystem is required for quality assurance and traceability. Such functionality is provided by the OIIE administration components.

Real-time Capability is required for data analysis and automated decision making to, for example, react to failures. This is supported in the OIIE by not requiring all communication to occur over an ISBM, which may not be real-time capable. This allows real-time systems to be directly connected to data sources for rapid decision making, while data and events are propagated more slowly across the OIIE to higher-level systems for other forms of analysis and decision making.

Service Orientation is present in the OIIE as the core standards upon which it is built have been designed using Service-Oriented Architecture principles. As such, the OIIE has been designed with service-orientation in mind. At the core sits the ISBM, which provides intra- and inter-Enterprise data exchanges through web services.

Modularity is natural to the OIIE as it is a federated distributed system that aims for plug-and-play capability of a variety of systems and software, including COTS. The core standards and specifications define interfaces and methods of data exchange, leaving the implementation details of individual components up to the organisations involved. This achieves maximum flexibility in the ecosystem by allowing an organisation to change components while maintaining interoperability across the ecosystem through the use of standardised interfaces, exchange mechanisms, and adaptors.

Security is provided by the OIIE in several ways. The core specifications define requirements that must be met in the OIIE such as the use of SSL/TSL for communication security; security tokens to manage the authorisation of systems to communicate across channels of the ISBM; role-based security for both people and systems in the OIIE; management provided by the OIIE Ecosystem Administrator.

Fulfilling these principles puts the OIIE framework in an excellent position to support IIoT environments and Condition-based Predictive Maintenance.

CONCLUSIONS

To the best of our knowledge, there is no open standards based framework which addresses CBPdM. In this paper, we explain the OIIE framework which supports the IIoT requirements and reuses existing open standards of CBM and EAI to support CBPdM. The OIIE-based architecture is at its core an interoperability solution that enables devices and systems to communicate effectively in both inter- and intra- enterprise contexts using a variety of standards, data models, and exchange protocols.

Interoperability of the asset management systems is crucial in achieving accurate diagnosis and prognosis as it can highly augment the data received from assets. Sensors can detect the slightest anomaly with respect to the standard behaviour. Performance of components are continuously monitored with the help of the data collected from the connected sensors. Sensors can track certain KPIs with the help of the IIoT. The digital twin of an asset is used for comparing the measured and trending values with ideal model values. Any deviation from the benchmark is easily detected and appropriate alerts or warnings are raised. Thus, the maintenance team is alerted for possible intervention before the equipment breaks down. This

leads to optimum decision-making, to improved intelligent industrial operations, and create new business value.

ACKNOWLEDGMENTS

This research was funded in part by the South Australian Premier's Research and Industry Fund grant no. IRGP 37.

REFERENCES

1. Rosmaini Ahmad and Shahrul Kamaruddin. 2012. An overview of time-based and condition-based maintenance in industrial application. *Computers & Industrial Engineering* 63, 1 (2012), 135–149.
2. Marcus Bengtsson. 2003. Standardization issues in condition based maintenance. *Department of Innovation, Design and Product Development, Mälardalen University, Sweden* (2003).
3. Stefan Berger, Georg Grossmann, Markus Stumptner, and Michael Schrefl. 2010. Metamodel-Based Information Integration at Industrial Scale. In *Proc. MODELS 2010*, Vol. LNCS 6395. Springer, 153–167. DOI: http://dx.doi.org/10.1007/978-3-642-16129-2_12
4. Benjamin S Blanchard, Dinesh C Verma, Dinesh Verma, and Elmer L Peterson. 1995. *Maintainability: a key to effective serviceability and maintenance management*. Vol. 13. John Wiley & Sons.
5. Mark Bowren. 2012. *Software framework for prognostic health monitoring of ocean-based power generation*. Florida Atlantic University.
6. Carl S Byington, PW Kalgren, Brian K Dunkin, and Bryan P Donovan. 2004. Advanced diagnostic/prognostic reasoning and evidence transformation techniques for improved avionics maintenance. In *Aerospace Conference, 2004. Proceedings. 2004 IEEE*, Vol. 5. IEEE, 3424–3434.
7. RV Canfield. 1986. Cost optimization of periodic preventive maintenance. *IEEE Transactions on Reliability* 35, 1 (1986), 78–81.
8. Bala Chidambaram, DG Gilbertson, and Kirby Keller. 2005. Condition-based monitoring of an electro-hydraulic system using open software architectures. In *Aerospace Conference, 2005 IEEE*. IEEE, 3532–3539.
9. Adolfo Crespo Márquez, P Moreu de León, JF Gómez Fernández, C Parra Márquez, and M López Campos. 2009. The maintenance management framework: A practical view to maintenance management. *Journal of Quality in Maintenance Engineering* 15, 2 (2009), 167–178.
10. Bram de Jonge, Ruud Teunter, and Tiedo Tinga. 2017. The influence of practical factors on the benefits of condition-based maintenance over time-based maintenance. *Reliability engineering & system safety* 158 (2017), 21–30.
11. Johannes Drever, Helmut Naughton, Michael Nagel, Andreas Löhr, and Matthias Buderath. 2016. Implementing MIMOSA Standards.
12. Danúbia Espíndola, Luca Fumagalli, Marco Garetti, Silvia Botelho, and Carlos Pereira. 2011. An adaption of OSA-CBM architecture for Human-Computer interaction through mixed interface. In *Industrial Informatics (INDIN), 2011 9th IEEE International Conference on*. IEEE, 485–490.
13. David Followell, Dan Gilbertson, and Kirby Keller. 2004. Implications of an open system approach to vehicle health management. In *Aerospace Conference, 2004. Proceedings. 2004 IEEE*, Vol. 6. IEEE, 3717–3724.
14. D. Grossmann, K. Bender, and B. Danzer. 2008. OPC UA based Field Device Integration. In *2008 SICE Annual Conference*. 933–938. DOI: http://dx.doi.org/10.1109/SICE.2008.4654789
15. Georg Grossmann, Gerald Quirchmayr, and Markus Stumptner. 2011. An Architectural Concept for the CIEAM Enterprise Bus. In *Proc. of World Congress on Engineering Asset Management (WCEAM)*. Springer-Verlag, 251–261. DOI: http://dx.doi.org/10.1007/978-0-85729-493-7_21
16. Hashem M Hashemian and Wendell C Bean. 2011. State-of-the-art predictive maintenance techniques. *IEEE Transactions on Instrumentation and measurement* 60, 10 (2011), 3480–3492.
17. Mario Hermann, Tobias Pentek, and Boris Otto. 2016. Design principles for industrie 4.0 scenarios. In *System Sciences (HICSS), 2016 49th Hawaii International Conference on*. IEEE, 3928–3937.
18. Mirka Kans and Diego Galar. 2017. The Impact of Maintenance 4.0 and Big Data Analytics within Strategic Asset Management. In *6th International Conference on Maintenance Performance Measurement and Management, 28 November 2016, Luleå, Sweden*. Luleå University of Technology, 96–103.
19. Mirka Kans, Diego Galar, and Aditya Thaduri. 2016. Maintenance 4.0 in Railway Transportation Industry. In *Proc. WCEAM 2015 (LNME)*. Springer, 317–331. DOI: http://dx.doi.org/10.1007/978-3-319-27064-7_30
20. Kirby Keller, Dave Wiegand, Kevin Swearingen, Chris Reisig, Scott Black, Alan Gillis, and Mike Vandernoot. 2001. An architecture to implement integrated vehicle health management systems. In *AUTOTESTCON Proceedings, 2001. IEEE Systems Readiness Technology Conference*. IEEE, 2–15.
21. Setrag Khoshafian and Carolyn Rostetter. 2015. Digital Prescriptive Maintenance. *Internet of Things, Process of Everything, BPM Everywhere* (2015).
22. Mitchell Lebold, Karl Reichard, and David Boylan. 2003. Utilizing DCOM in an open system architecture framework for machinery monitoring and diagnostics. In *Aerospace Conference, 2003. Proceedings. 2003 IEEE*, Vol. 3. IEEE, 3_1227–3_1236.

23. Mitchell Lebold, Karl Reichard, Carl S Byington, and Rolf Orsagh. 2002. OSA-CBM architecture development with emphasis on XML implementations. In *Maintenance and Reliability Conference (MARCON)*. 6–8.

24. CKM Lee, Yi Cao, and Kam Hung Ng. 2017. Big Data Analytics for Predictive Maintenance Strategies. In *Supply Chain Management in the Big Data Era*. IGI Global, 50–74.

25. Jay Lee, Ramzi Abujamra, Andrew KS Jardine, Daming Lin, and Dragan Banjevic. 2004. An integrated platform for diagnostics, prognostics and maintenance optimization. *Proceedings of the intelligent maintenance systems* (2004), 15–27.

26. Kang Lee. 2000. IEEE 1451: A standard in support of smart transducer networking. In *Instrumentation and Measurement Technology Conference, 2000. IMTC 2000. Proceedings of the 17th IEEE*, Vol. 2. IEEE, 525–528.

27. Avin Mathew, Ken Bever, Michael Purser, and Lin Ma. 2012. Bringing the MIMOSA OSA-EAI into an Object-Oriented World. In *Engineering Asset Management and Infrastructure Sustainability*. Springer, 633–646. DOI: http://dx.doi.org/10.1007/978-0-85729-493-7_49

28. Avin Mathew, Liqun Zhang, Sheng Zhang, and Lin Ma. 2006. A review of the MIMOSA OSA-EAI database for condition monitoring systems. In *Engineering Asset Management*. Springer, 837–846.

29. MIMOSA. 2018. OIIE Information and Systems Architecture. (2018). http://www.mimosa.org/oiie-information-and-systems-architecture

30. Venkatraman Narayan. 2012. Business performance and maintenance: How are safety, quality, reliability, productivity and maintenance related? *Journal of Quality in Maintenance Engineering* 18, 2 (2012), 183–195.

31. Rolf F Orsagh, Christopher J Savage, and Kathy McClintic. 2001. *Development of Performance and Effectiveness Metrics For Mechanical Diagnostic Technologies*. Technical Report. Impact Technologies LLC Rochester NY.

32. ABI Research. 2014. Maintenance Analytics to Generate $24.7 Billion in 2019, Driven by Predictive Maintenance and Internet of Things. (22 March 2014). https://www.abiresearch.com/press/maintenance-analytics-to-generate-247-billion-in-2/.

33. Aileen Richardson, Dale Keairns, and Briggs White. 2018. The role of sensors and controls in transforming the energy landscape. In *Micro-and Nanotechnology Sensors, Systems, and Applications X*, Vol. 10639. International Society for Optics and Photonics, 106390Y.

34. Michael J Roemer, Gregory J Kacprzynski, Andrea Palladino, Thomas Galie, and Carl Byington. 2001. *Prognostic enhancements to naval condition-based maintenance systems*. Technical Report. Impact Technologies LLC Rochester NY.

35. Mickey Shroff, Jyrki Keskinen, Oskar Norrback, Sakari Junnila, Jaakko Takaluoma, and Pasi Tuominen. 2011. MIMOSA and OPC UA applied in wapice remote management system. In *Automaatio XIX seminar*, Vol. 3.

36. Tarapong Sreenuch, Antonios Tsourdos, and Ian K Jennions. 2013. Distributed embedded condition monitoring systems based on OSA-CBM standard. *Computer Standards & Interfaces* 35, 2 (2013), 238–246.

37. Kevin Swearingen, Wayne Majkowski, Brian Bruggeman, Dan Gilbertson, Jon Dunsdon, and Ben Sykes. 2007. An open system architecture for condition based maintenance overview. In *Aerospace Conference, 2007 IEEE*. IEEE, 1–8.

38. Sumant Tambe, Abdel-Moez E Bayoumi, Alex Cao, Rhea McCaslin, Travis Edwards, and Condition-Based Maintenance Center. 2015. An Extensible CBM Architecture for Naval Fleet Maintenance Using Open Standards. In *Intelligent Ship Symposium, Boston, USA*.

39. Michael Thurston and Mitchell Lebold. 2001. *Standards developments for condition-based maintenance systems*. Technical Report. Pennsylvania State Univ University Park Applied Research Lab.

40. Antti Tuomi. 2010. *Application integration for condition based maintenance*. Ph.D. Dissertation. Master Thesis, Aalto University School of Science and Technology, Faculty of Electronics, Communications and Automation Espoo, Finland, 12.5.

41. Shiyong Wang, Jiafu Wan, Daqiang Zhang, Di Li, and Chunhua Zhang. 2016. Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. *Computer Networks* 101 (2016), 158–168.

42. Theodore J. Williams (Ed.). 1989. *A Reference Model For Computer Integrated Manufacturing*. Instrument Society of America. http://www.pera.net/Pera/PurdueReferenceModel/ReferenceModel.html