Device Status Information Service Architecture for Condition Monitoring Using OPC UA

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Abstract—Condition monitoring and maintenance of devices and equipment is an important aspect of operating a production facility affecting the availability of production systems. Modern production environments can consist of thousands of devices that each need to be monitored so that maintenance can be performed when necessary to sustain a cost-effective state of production. Today operation and maintenance (O&M) is typically outsourced, and equipment and device manufacturers have also entered the service business. This brings challenges in managing a multitude of different devices using different protocols as well as in the varying needs for utilizing this information in enterprise functions and services. Based on OPC Unified Architecture (UA) a scalable architecture is developed for providing device status information of heterogeneous field devices and sensors to enterprise level applications and services. A proof of concept implementation of this architecture is presented and its envisioned adoption in a mine environment is discussed.

I. INTRODUCTION

Factories and production environments consist of thousands of devices and other equipment that make up the efficient and highly optimized production system. One of the key factors influencing productivity and efficiency is the availability and correct operation of individual devices and the system as a whole. Suboptimal performance of the equipment can cause quality defects and as a long-lasting condition also significant costs, e.g. in terms of increased energy consumption.

Industrial information and control systems operate and monitor the status of production processes. The same networks and fieldbuses that connect the devices can also be used for monitoring the status of individual devices. For this purpose there are typically separate condition monitoring systems querying the status and condition of intelligent field devices. This enables operation and maintenance (O&M) to rely on condition based maintenance (CBM) [1], which can be seen as one optimized maintenance strategy based on the actual need. CBM allows balancing maintenance costs with production performance and increased knowledge of the risk of failure.

The typical maintenance strategy in modern facilities includes both planned maintenance and CBM, the combination of which is often referred to as preventive maintenance. Data is gathered in order to develop models that can be used in evaluation and simulation to make accurate estimates when maintenance is required. Various after-sales services are also available to support operations. This raises needs to process and analyse device data, and to integrate functions to internal and external (cloud) services. Together with timely device information these models allow further optimization of O&M activities that ultimately pave the way for availability-oriented business models [2]. Corrective maintenance actions are still probable as sudden failures occur. However, also then it is beneficial to have up-to-date device data for deciding whether to perform additional maintenance if downtime is inevitable.

The shift in operation models has introduced the use of services to core functions such as maintenance, and the operative work can be distributed among a number of service providers. In addition, manufacturers of devices and equipment are increasingly breaking through with their own services and after sales support that depend on this real-time information [3]. Technologies enable access to data across organizational boundaries but this raises concerns on privacy, information security and trust [4]. Another major challenge in product lifecycle information management is to get the right insight from the constantly increasing data available.

In industrial settings there are typically devices and equipment in the field from several vendors that are connected using different fieldbuses and protocols, and also over the Internet – sometimes also referred to as the Industrial Internet of Things. Different technologies have their redeemed place fulfilling specific needs but concurrent use of a multitude of technologies complicates integration as a consequence. In addition, system interfaces may differ as well as the device descriptions and data provided by the devices. This calls for middleware solutions and architecture that realize the service oriented architectures (SOA) of tomorrow, i.e. support dynamic system interactions, enhance interoperability and utilization of information, and adapt to different needs in various applications.

This paper presents work that is being done as a part of the Arrowhead project related to a pilot case for condition monitoring of devices in a mining environment. An architecture concept is proposed for providing uniform access to heterogeneous field device and sensor information of varying kind including legacy systems. An additional requirement is scalability up to thousands of devices while still being able to provide information in near real-time for condition monitoring applications and O&M services. The resulting solution
constitutes a service for the Arrowhead framework that, as a technological service infrastructure, addresses challenges associated with cooperative systems and services in automation.

Requirements and motivation for developing the new architecture for maintenance related services in constrained production environments such as mines are outlined in section III. A solution based on OPC UA (Open Platform Communications Unified Architecture) is proposed in section IV and the proof-of-concept implementation is described in section V. A preliminary evaluation of the solution also assessing the features and capabilities of OPC UA is given in section VI before concluding the paper in section VII. The main contributions of the paper are the architecture concept for condition monitoring in large but constrained production environments, and the early results and evaluation of how the OPC UA based proof of concept implementation addresses those requirements.

II. RELATED WORK

To cope with production site restrictions and reduce data transfers a method aggregating data at field device level has been demonstrated [5]. In the proposed solution all data is processed at the device and Web Services are used for clients to access only relevant data. The authors stated at the time being that only simple Web Service operations can be performed due to the limited resources of devices. A business processes based condition monitoring application relying on Web Services and Devices Profile for Web Services (DPWS) for device communication has been presented in [6]. In another study a concept of Evolvable Production Systems has been introduced that based on an open SOA infrastructure supports the setup, deployment, management, supervision and diagnosis of devices throughout their lifecycle [7].

An IoT based SmartFactory initiative has been created where production functions including maintenance form a system of loosely coupled self-adapting modules [8]. To cater for the needs of data federation required in Internet of Things and Services (IoTS) the Aletheia distributed semantic data integration system has been developed [9]. The use of ontology semantics to analyse and improve interoperability of industrial systems has been expressed for example by [10], [11] and [12].

FDT (Field Device Tool) and DTM (Device Type Manager) standardize the communication and configuration interface between intelligent field devices and control systems. For this an open frame application has been developed that takes full advantage of the specification by making available all data regardless of communication profiles or devices [13]. A standardization effort similar to FDT is FDI (Field Device Integration) that bases its descriptions on EDDL (Electronic Device Description Language). FDT is to a large extent interoperable with FDI that will replace the former in the future [14]. Interestingly, before deciding the fate of the competing standards OPC UA was suggested to unify the different models and ease distributed control system (DCS) integration [15].

The use of Web Based Enterprise Management (WBEM) has been proposed for device-by-device maintenance of intelligent field devices [16]. In the approach the information model has been extended and prototyped with PROFIBUS and PROFINET fieldbuses. In an OPC UA roadmap UA has been used as an adapter gateway for classic OPC DA integrated HART field device communication [17].

OPC is the de facto standard for industrial integration in process industry and the increased potential of UA covers a broad range of industrial applications and services. For example in condition monitoring applications OPC UA has been studied by [18] where it was used for SOA integration and enterprise asset management in maintenance. It has also been demonstrated that IEC 61499 application models for an ISA-88 batch process can be translated to the OPC UA address space model for value added applications [19].

III. REQUIREMENTS AND MOTIVATION FOR CONDITION MONITORING IN CONSTRAINED ENVIRONMENTs

In this paper a mine environment is used as the reference for requirements many of which are also typical to other processing environments. Mines are sites that operate for a long time (the intended life-time is typically longer than a power plant or paper mill). The longer a mine or some other processing facility operates the higher the probability to end up having multiple systems in concurrent operation. In the best case they are from one vendor, i.e. different generations or versions. The reality often is the site owner ending up with multiple systems from different vendors running in various locations and controlling different parts of the process.

In these kinds of environments interoperability and legacy system integration & communication could affect the mine production and maintenance dramatically. The production shall run with the highest productivity and quality without any unpredictable service breaks. Computerized maintenance systems should plan and ensure scheduled maintenance for the critical process devices. In the field there are already smart equipment that support intelligent communication protocols and thus can give more information than just basic measurement data. The smart devices can report multiple field diagnostics and internal self-tests can also detect other problems. As fieldbus protocols can transfer this additional information to the system level it should be available to end users (operators or maintenance personnel) immediately and in an understandable format.

There are cases where network bandwidth is limited and all data cannot be stored e.g. in control systems or in cloud services as a point of interaction or for later data analysis. Lightweight protocols can be used to push data more efficiently but it is not always possible to equip legacy devices with such features. The connection may also be temporarily interrupted but critical information should still be transferred once connectivity is restored. Intelligent field devices and many embedded devices are typically constrained concerning computational resources also limiting on-device computation.

A. A Multitude of Devices

Integration of systems is not easy nor always even possible when creating intelligent services in modern automation systems with multiple vendors. Devices can be integrated from the systems with additional hardware but not as easily as it should be possible. For example, as Hart devices are connected to DCS systems there are cases where they are connected to a separate Hart network just to collect & bind information to condition monitoring systems. As there are multiple Hart
devices they are often delivered from multiple vendors. Even though Hart or any other fieldbus protocol is standardized, and interoperability is tested & guaranteed, it is not the whole story. Each vendor can provide extra features and in many cases these require their own commands for the extra diagnostics information which as a consequence complicates information integration between devices. Fortunately many systems can be extended to support these and mapping tools are available that can e.g. help end users to access all device specific parameters.

As we move from older fieldbus protocols like Hart and Profibus to new wireless protocols we are facing more new features than ever. Devices can decide for themselves the communication time and new devices can adjust the communication to optimize their energy usage. The more independence is given to the device itself the more intelligence and features are needed on the host system as well. Most of the communication can be solved on the communication stack level but the content and how to use it must still be implemented at the application level. As devices can be more flexible and dynamic the requirements are challenging for system providers as each system needs to be able to handle more complex scenarios. A solution could be a system that can be extended on the meta level, e.g. with parameters and semantics that can be extended.

B. Utilization of Information

The actual problem is connecting information from the devices at the systems level. This is the main challenge to solve. As each system has its own point-to-point connection hardware for devices or their own implementation for standard fieldbus protocols the actual information flow to the next level or other system is not open or truly standardized.

The integration requirements comprise not only internal manufacturing execution system (MES) and enterprise resource planning (ERP) functions but also service providers and device vendors offering O&M services. The information needs can thus be external to the facility and possibly concern multiple competing service providers. This introduces concerns on security, trust and confidentiality of sensitive information.

C. Need for Information Models and Semantics

Standards and agreed definitions are essential for interoperability of systems and compatibility of services. It is natural to have several different and possibly overlapping and competing standards to support the various needs in different domains and application areas. Acknowledged standards and information models that have been adopted by the industry promote information exchange. Examples of information models and standards applicable to O&M are, for example, MIMOSA [20] for condition monitoring and IEC 62264 (ANSI/ISA-95) [21] concerning maintenance operations.

Well defined concepts and lexical semantics are a prerequisite for unambiguous information interpretation. This in turn enables mediation of information with mapping and transformation of data structures and the use of adapters between different systems. In a service environment consisting of multiple service providers and consumers information interoperability is emphasized. The use of Semantic Web technologies in combination with service-oriented technologies has been considered very promising for future software architectures and next generation computing infrastructure [22].

IV. INFORMATION SYSTEM ARCHITECTURE BASED ON OPC UA

The current need for more effective, secure, and reliable flow of information from the process level to the management level in distributed systems is justified by the extensive volume of information, the limited bandwidth and communication networks available at lower levels, and the stricter demand for on-time information. Also, the increasing number of intelligent devices from different vendors impose higher scalability and interoperability requirements making integration in industrial automation applications challenging especially in small systems and costly in larger systems. Answering these needs OPC UA aims to promote operational effectiveness by providing a platform independent standardized interface between different systems and vendors. This section introduces the OPC UA based architecture concept for integrating heterogeneous device information from the lower levels to O&M applications.

A. Standard Access and Communication Protocol

Classic OLE (Object Linking and Embedding) for Process Control (OPC) is a set of standard interfaces that allow any client to communicate with any OPC compatible device using the Microsoft-based COM/DCOM technology. While this older standard handled the need for interoperability at control level it also had severe limitations such as: Microsoft Windows platform dependency, security, no control over COM/DCOM, and poor configurability. Extending the proven functionality of Classic OPC and overcoming its problems, a new communication technology standard - OPC Unified Architecture (UA) - was first published in 2006 by the OPC Foundation. Since then the acronym has also stood for Open Productivity and Connectivity before the current Open Platform Communications.

Based on a cross-platform SOA for process control, OPC UA enables data acquisition, information modelling and communication between the plant floor and the Enterprise, reliably and securely. It responds to the higher need of standardization and interoperability all the way up to the enterprise level by defining a uniform address space model with support for custom information models accessible via two protocols: a binary protocol that employs minimal resources and a Web Service protocol (SOAP) using standard HTTP/HTTPS. The XML Web Services protocol allows straightforward integration to other typical SOA applications while the binary UA protocol enables efficient and low bandwidth secure communication e.g. to plant floor level applications.

Integrating the existing OPC specifications, i.e. Data Access (DA), Alarms and Events (A&E), Historical Data Access (HDA), Discovery, Commands, Complex Data, and Object Types, in a single specification, OPC UA offers a broader scope of connectivity and application domains. It can also reduce system integration costs by providing a platform independent common architecture for accessing information. OPC UA ensures reliability through configurable timeouts, error detection, and communication failure recovery providing inter-vendor application redundancy. It is secure by default, using message encryption and endpoint authentication by means of advanced certificate handling. Easy configurable and maintainable, OPC UA is legacy-friendly allowing to interconnect proprietary field buses and wrap different existing protocols, and ready for future protocols that might need to be OPC unified [23].
B. Built-In Information Security

Information security is of critical importance when dealing with multiple partners, systems and technologies. For example the result of data corruption in ERP or a MES of a large enterprise could be disastrous [24]. Overcoming such risks, the complete UA Security Architecture consists of certificate based authentication and authorization, full message encryption and digital signing for data integrity, at three different levels: Application Layer (User Authorisation and Authentication - OPC UA Session), Communication Layer (Application Authentication - Secure Channel), and Transport Layer (Confidentiality and Integrity - Communication Protocol). Such measures allow secure transporting of sensitive data through different and unknown (possibly unsecure) networks [25].

Both OPC UA implementation protocols offer similar security options for using them simultaneously and transparently to the application layer [26]. The XML Web Service protocol is fully compatible with the WS Security specifications or the standard SSL Security whereas the binary protocol implementation, UA Secure Conversation, adapts identical procedures.

C. Hierarchical Aggregation

The number of data nodes, devices, assets, and sites that an enterprise has to manage nowadays may grow rapidly. A hierarchical aggregation of data is beneficial because:

- The systematic organization of data brings clarity to an otherwise very complex view
- Only relevant data is made available at each level, therefore reducing the amount of data being transferred between levels (i.e. saving bandwidth) and allowing to concentrate only on meaningful data
- It handles well dynamic systems that might scale horizontally and/or vertically
- It hides the device vendor complexity usually encountered at the plant floor levels

Data aggregation means processing and composing data from several sources. This implies understanding the underlying data structures e.g. in order to read data from different devices and present it uniformly to upper level applications and services. Adapters are used for this that utilize information model semantics in the processing and transformations.

D. Information Modeling

One of the most important improvements in UA is the information modeling specified in specification part 5 [27]. While the address space model offers a uniform way to browse and represent objects to clients it is the information model that provides a standardized set of nodes, types and references for constructing the data semantics. References can be used to declare relationships between nodes and Attributes are used to express node characteristics. These node and reference types can be extended with sub-types that enable construction of objects for different needs and development of domain-specific information models with semantics (Fig. 1).

Type information and the data object structures exposed by the server are modeled similarly. This and the fact that information models are persisted on the server allow clients to dynamically browse the address space and piece together the modeled data. In addition to directly browsing the node hierarchy also references can be used to traverse nodes and identify objects of interest. This enables fully dynamic behavior of OPC UA applications when new objects can be detected and the clients and the servers can be adapted to this.

OPC UA leaves a lot of room for device vendors to implement their own vendor-specific structures. This can introduce risks of developing overlapping or possibly incompatible structures and semantics. However, elements and definitions of existing standards can be used in the information modelling. Examples of such use of the information model are the building automation standard BACnet [28] and the power system automation standard IEC 61850 [29]. In addition, there are several companion standards in preparation such as the OPC UA based ANSI/ISA-95 MES/ERP integration [30].

Considering the requirements identified in the previous section the MIMOSA Condition Based Maintenance (CBM) standard [20] is a candidate for condition monitoring data management. MIMOSA Enterprise Application Integration [31] is also considered for asset modeling. MIMOSA CBM is advantageous because it offers a device vendor independent yet acknowledged model for specifying condition monitoring data for enterprise level systems. This has also been discussed by [32] but not fully implemented due to performance reasons. The CBM specification is broad but allows utilizing only those parts that are needed in the application. One can also specify own concepts if required.

From the OPC UA viewpoint MIMOSA is seen as the information model specification that as a standard defines concepts and structures to be used. When the MIMOSA model is implemented according to OPC UA meta modeling principles the information model can be browsed and discovered as previously described. Information models can be seen as data representations for different domains or purposes. An OPC UA server is able to concurrently expose several different information models that can in the end reflect the same physical devices and values. Information models can also be developed that connect data together for some specific purpose thus eliminating any unnecessary information.
V. PROOF OF CONCEPT IMPLEMENTATION

To demonstrate the feasibility of OPC UA in enabling interoperability and hierarchical data exchange at the enterprise level, a proof-of-concept is being built as shown in Fig. 2. Using an aggregation architecture, Enterprise C (TUT) is able to monitor process data and events from two different partners: Enterprise A (Metso) and Enterprise B (Wapice). Without any prior knowledge of the data from the other two enterprises (i.e., legacy protocols used to acquire the data, data storage format, processing methods, etc.), Enterprise C was able browse the OPC UA Server address spaces, discover their data models, and based on this develop alarms to be triggered to the upper levels. As a result the OPC UA Server of Enterprise C exposes the full address spaces of both nested servers. More importantly it also provides a generic view that, using mapper adapters, unifies and generalizes information of different types of devices for condition monitoring applications.

A. Integration of Field Devices and Sensors

Metso has implemented an OPC UA server running on BeagleBone Black (BBB). In this implementation, Metso uses BBB as an embedded server device and TI SensorTag as a Bluetooth client device. Prosys OPC UA Java SDK is used to implement the OPC UA server for relaying data to the aggregating OPC UA server, or any other applications. On the BBB there is also a Node.js server to get the data from TI SensorTag through the Bluetooth Low Energy (BLE) protocol. After the data is obtained, Node.js pushes the data to a HTTP server UI. Meanwhile, a TCP server in Node.js is ready for communicating to the Java OPC UA server using a TCP client. As a result raw sensor data is transmitted in TCP socket traffic between the two servers in the BBB system. The Node.js server application and the Java OPC UA server run in parallel. Moreover, the Java OPC UA server can get status data from MetsoDNA using EDR socket based communication. Fig. 3 shows the system communications.
To replace the battery of e.g. a wireless BLE sensor. can then be interpreted as the need for a maintenance action in condition monitoring applications on the enterprise level this battery voltage is below a given threshold. As an event in information. An example of an active condition is when the and Conditions [33] an event model for relaying event based mechanism for propagating status notifications upwards is also being developed. OPC UA defines in the specification part 9 Alarms and Conditions [33] an event model for relaying event based information. An example of an active condition is when the battery voltage is below a given threshold. As an event in condition monitoring applications on the enterprise level this can then be interpreted as the need for a maintenance action to replace the battery of e.g. a wireless BLE sensor.

Fig. 5. Envisioned scaling of aggregate servers. Upper-level servers expose the address space of nested servers but also the generalized device status views.

To achieve this a generic information model that presents data from different devices in a uniform manner is being developed. However, as illustrated in Fig. 1, there are also device specific type representations available as all relevant device data, at least at the moment, cannot be expressed in the generic model. The rationale is to use the information modelling capabilities to adapt legacy system structures for improved interoperability. The device specific information models are made up from device descriptions and those information models are then used for the consolidating generic model. A more detailed presentation of the information model including the notification event model will be presented later as the work is still evolving and the utilization of concepts from existing standards such as MIMOSA is being investigated.

Fig. 2 presents the top-level OPC UA applications as a one-tier client/server architecture. However, the architecture can be scaled to multiple intermediary levels of chained servers as illustrated in Fig. 5. Fieldbus level on-line monitoring of a large number of individual devices, for example, can be slow which instead benefits from several horizontally parallel servers each dedicated to their own process segment or group of devices. An OPC UA server can host a large number of field devices and sensors but the performance depends on hardware resources and device communications. The computational capacity in the field and in typical rack controllers is limited. Therefore it is often better to utilize multiple servers and aggregation levels in between to provide the already once collected information to the different applications on upper levels.

To further reduce unnecessary communication a mechanism for propagating status notifications upwards is also being developed. OPC UA defines in the specification part 9 Alarms and Conditions [33] an event model for relaying event based information. An example of an active condition is when the battery voltage is below a given threshold. As an event in condition monitoring applications on the enterprise level this can then be interpreted as the need for a maintenance action to replace the battery of e.g. a wireless BLE sensor.

VI. DISCUSSION

OPC UA is a technology for industrial system integration that embeds advanced information modelling capabilities for developing expressive domain and application specific models. It is well suited for integration of devices and systems with MES and ERP level applications and services. Compared to other protocols often used in devices OPC UA offers enterprise level security and reliability on the application level. Many lightweight protocols perform better from a resource consumption and throughput point of view but often lack the security and reliability that is required in many industrial settings. The use in resource constrained embedded devices is facilitated with the native OPC UA binary protocol.

The OPC UA based solution concept provides uniform access to different kinds of distributed multivendor devices and sensors. This allows treating them similarly when implementing new enterprise services and centralized condition monitoring functionality. Information modelling capabilities are used in addition to the unified general device view also to provide device specific data for those that benefit from e.g. fieldbus protocol details exposed through the address space of lower level servers. The solution further enables creating specific views that e.g. dynamically show devices requiring attention or having active events. The dynamicity of the address space also allows connecting new devices without the need to make any adjustments to the top-level aggregations or the enterprise applications and services that ultimately use this information.

It is likely that the number of stakeholders with production and device related information needs will continue to increase. The solution supports using OPC UA security for system and communication authentication, access authorization as well as encryption of technical business data in an environment of competing device vendors and service providers. This, however, requires additional infrastructure services e.g. to manage certificates, and this also affects the implementation of the client and server applications.

The solution reduces network traffic and shortens the cycle time of querying a large number of devices when distributed on horizontally parallel servers. This is also expected to alleviate limited bandwidth but on the other hand requires more functionality on lower system levels. However, it does not solve all challenges related to limited network bandwidth e.g. in cases where it would be desirable to gather all device data for later data analysis. An alternative is then to perform the analysis on the lower service levels and instead of raw data only provide refined information upwards. This in turn incurs further burden of managing distributed analysis features such as in the case of identifying drifting values of similar device types. Another option that might be sufficient in many cases is to push buffered data periodically when network bandwidth is available. Storing data locally and offering historic data services is also expected to be feasible on lower aggregation levels but storage capacity can often be restricted.

In the context of a system of services OPC UA can be positioned as a technology for implementing SOA. In larger compositions, such as the Arrowhead framework being developed, a OPC UA based solution offers in addition to a standard interface protocol also means for describing communication
semantics. Nevertheless, responsibilities remain for the service infrastructure to provide supporting service registry functionality, service governance, adapter services as well as testing and simulation features to validate compositions in order to assure interoperability and flexible use of interchangeable services.

VII. CONCLUSION

This paper outlined requirements for the concept of an information system architecture for condition monitoring of field devices and sensors. A mine condition monitoring environment is used as a point of reference for requirements similar also to many other production facilities. An OPC UA based solution is proposed for implementing the system architecture, integration and aggregation of heterogeneous device information, and for finally providing this to enterprise level condition monitoring applications and services in a uniform manner. A proof of concept implementation is described that unifies device status information directly from field devices and sensors as well as from devices accessed through a cloud service interface.

The work presented is an ongoing effort part of a pilot case in the Arrowhead project. Future work will focus on further developing the device and event information model for the needs of the pilot. Integration to condition monitoring applications utilizing the information and other enterprise level services of the framework will also be developed in the future.

REFERENCES


