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On architecting and composing through-life engineering information services to enable smart manufacturing

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Abstract

Engineering information systems play an important role in the current era of digitization of manufacturing, which is also known as smart manufacturing. Traditionally, these engineering information systems spanned the lifecycle of a product by providing interoperability of software subsystems through a combination of open and proprietary exchange of data. But research and development efforts are underway to replace this paradigm with engineering information *services* that can be composed dynamically to meet changing needs in the operation of smart manufacturing systems. This paper describes the opportunities and challenges in architecting such engineering information services and composing them to enable smart manufacturing.

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Keywords: Through-life engineering; information services; standards; architectures; service composition; SOA.

1. Introduction

In a keynote paper at the 2nd International Through-life Engineering Conference, McMahon and Ball [1] addressed the role of information systems in improving the through-life support of long-lived, complex artifacts. They pointed out the promise offered by information systems in a number of areas including productivity and more accurate and responsive assessment of artifact conditions. They also stressed the need for understanding the complexity and interlinked nature of the engineering information involved in through-life engineering services.

In this paper, we delve a little deeper into the engineering information that is shared among different phases in a product's lifecycle and across its supply chain. We also explore how different aspects of the information can be offered as services. In particular, we examine the role of open engineering information and messaging standards that are relevant to through-life engineering services.

The idea of sharing engineering information as services is not new [2, 3]. When web services – supported by service-oriented architecture (SOA) – became a reality more than a decade ago, such engineering information services offered an attractive, alternative avenue to integrate various engineering activities. Since then, two major developments have accelerated this trend. The first is the wide-spread realization that the entire manufacturing sector is being digitized, which positions information at the front and center of all modern manufacturing. This, in turn, has also heightened the need for engineering information standards in the manufacturing sector. The second is the virtualization of computing and communication resources using 'clouds,' which has moved the engineering service functions to the clouds with several attendant opportunities and challenges.

We start by setting the stage with the modern digitization of manufacturing in Section 2. This is also referred to as smart manufacturing. Section 3 positions several standards, some of which have been extensively updated recently, as exemplar enablers of smart manufacturing systems. Section

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4 provides a brief introduction to service-oriented architecture, which can be used to compose various engineering information services to implement a scenario such as the one described in Section 5. Some concluding remarks are made in Section 6 after a brief summary.

2. Digitization of manufacturing

In April 2012, the Economist magazine published an influential article that proclaimed that the Third Industrial Revolution, in the form of digitization of manufacturing, is well underway [4]. By its reckoning, the first industrial revolution began in Britain in the late 18th century, with the mechanization of the textile industry. The second industrial revolution came in the early 20th century, when Henry Ford mastered the moving assembly line and ushered in the age of mass production. In the third industrial revolution currently under way, manufacturing is going digital.

A year later, using a slightly different counting method, the German manufacturing industry came up with the nickname Industrie 4.0 to refer to the current era in manufacturing [5]. By its count, the first three industrial revolutions came about as a result of mechanization, electricity, and information technology. Now, the introduction of Internet of Things and Services into the manufacturing environment is ushering in a fourth industrial revolution called ‘Industrie 4.0.’ The German manufacturing industry predicts that in the future, businesses will establish global networks that incorporate their machinery, warehousing systems, and production facilities in the shape of Cyber-Physical Systems (CPS).

Irrespective of how we choose to count, it is clear that a new manufacturing era is upon us and it is driven by information – a lot of information, more popularly known nowadays as ‘big data.’ In an opinion piece in a special issue of the Economist magazine, the chief executive of IBM argued that data is the natural resource for the 21st century – just as steam power was for the 18th, electricity for the 19th, and hydrocarbons for the 20th [6]. She predicted that a new model of the firm will rise in 2014 using data as the natural resource, and called it the ‘smarter enterprise.’

While the private sector is preparing to exploit the digitization of manufacturing, many countries are investing in public-private partnerships to stimulate manufacturing innovation and get ahead in the new era. The United Kingdom has set up sixteen Centres for Innovative Manufacturing. They range from Additive Manufacturing to Ultra Precision, including Through-life Engineering Services. The German government, manufacturing industry, and academia are teaming up under the ‘Industrie 4.0’ umbrella and are investing to preserve their manufacturing leadership. Several Fraunhofer Institutes have demonstrated successfully the German model of public-private partnership to bring scientific ideas to industrial practice.

Since 2012, the United States of America has embarked on a major investment in a national network for manufacturing innovation [7], starting with four public-private partnership institutes. More such institutes are expected to join the national network soon. Several U.S. national research laboratories, including the National Institute of Standards and Technology (NIST), are investing in manufacturing-related research and development projects. In particular, NIST is investing in Smart Manufacturing, which is characterized by a heavy use of information, communication, and network technologies as befitting the needs of the new manufacturing era. Some of the enablers of smart manufacturing systems are described next.

3. Standards to enable smart manufacturing systems

Smart manufacturing systems require semantic representations of engineering information that are machine readable. However, the tradition of engineering drawings and textual documents still dominate engineering practice throughout a product’s lifecycle. Even if the venerable paper is replaced by a (portable) display screen, the computer generated drawings (e.g., using a computer-aided drafting system) and rich-text files (e.g., using a modern word processing system with graphics) are the means by which much of the information is communicated to through-life engineering services. This then requires human reading and interpretation, which are error prone and time consuming.

Smart manufacturing systems demand something better. They require engineering drawings to be replaced by augmented, three-dimensional (3D), geometric models; and, rich-text files to be replaced by information models of products and processes. These replacements enable machine readability that results in fast and error-free processing of engineering information from the beginning to the end of a product’s lifecycle.

Recent developments in standards provide some of the necessary tools and technologies to move towards machine readability. It is clear that no single software vendor or organization can cover the entire breadth and depth of a product’s lifecycle. So, standards have emerged as the natural choice to link disparate software systems and services. We describe some examples of the enabling standards in the following subsections.

3.1 Model-based 3D engineering

The International Organization for Standardization (ISO) has completed a major effort on a new standard ISO 10303-242 titled ‘Managed Model Based 3D Engineering.’ It belongs to a family of standards called STEP (STandard for the Exchange of Product model data). ISO 10303-242 is also called the STEP Application Protocol 242 (STEP AP 242, for short). STEP AP 242 combines many of the functionalities of its predecessors AP 203 and AP 214, and offers more [8]. Some of the new and improved functionalities in STEP AP 242 that are of interest to through-life engineering support are described below.

Product Manufacturing Information (PMI) is a phrase used by the Computer Aided Design and Manufacturing (CAD/CAM) community to refer to Geometric Dimensioning and Tolerancing (GD&T), surface texture, finish requirements, process notes, material specifications, welding symbols, and other annotations. Some of this information is also referred to as Geometrical Product Specifications (GPS), especially in the ISO parlance. PMI is also expanded as Product and Manufacturing Information, but the intent still remains the same. Fig 1 illustrates an example of presentation of PMI on a 3D model.

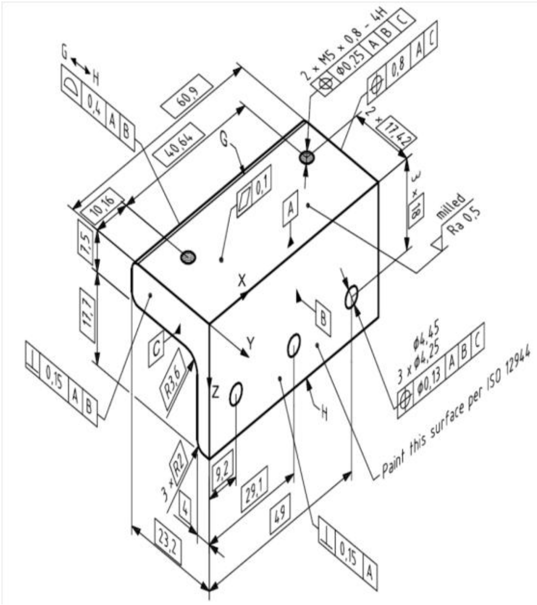

Fig. 1. An example of standardized presentation of product manufacturing information (PMI) on a 3D model.

STEP AP 242 PMI takes the first major step towards replacing two-dimensional engineering drawings with 3D models. More information on this new and exciting development can be found in [9]. It is interesting to note that the strongest business case for standardized PMI semantic representation originally came from the LOTAR (LOng Term Archival and Retrieval) effort [10]. LOTAR, which is led by the aerospace industry, hopes to make the engineering information available in machine readable form well into the later phases of a product's lifecycle.

Even though the urge to archive 3D models with PMI was triggered initially by aerospace regulatory requirements, its appeal to all through-life engineering services goes well beyond aerospace industry. In fact, any effort to remanufacture or reproduce anew a product or component during its use-phase requires PMI well after its initial manufacture. In particular, as we will describe in Section 5, several through-life engineering services require access to geometrical information about complex, long-lived products – preferably in 3D.

Recent developments in manufacturing technology have made archived, 3D models even more valuable. For example, additive manufacturing, also known as 3D printing, has provided a greater ability to manufacture one-off or small-lot production of parts economically. But, to exploit the 3D printing technology for maintenance, repair, and overhaul, it is important to retain 3D models of parts – preferably in a neutral, standardized format – for a long period.

The same pressure that drove industry to seek standardized PMI representation also pushed the development of a standardized representation of composite structures in STEP AP 242. Fig 2 shows a complex, composite structure that contains several layers of resin-impregnated fibres and embedded components. In addition to the final 3D structure, STEP AP 242 composites representation retains the lay-table information that is critical for manufacturing. More details on the recent STEP composites capabilities can be found in [11].

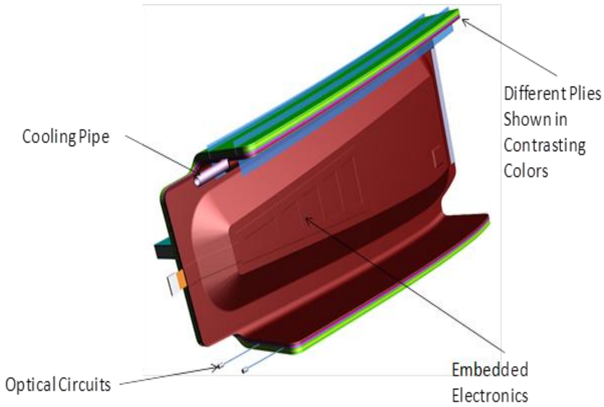

Fig. 2. An example of complex, composite structure representable by STEP AP 242.

As more products, especially in the aerospace sector, are manufactured using composite materials, their engineering information should be available in machine readable form for through-life engineering services. Repairing a damaged composite structure in service, for example, is no easy matter. It requires detailed information about the layers, ply orientations, and other embedded components to bring the damaged structure back to service quickly and correctly.

Another new capability in STEP AP 242 is the Business Object Model (also known as the BO Model), which represents much of the standardized meta-data associated with a product. BO model contains, for example, the assembly structure of a complex product. This assembly model, when combined with detailed 3D PMI for components of an assembly, provides a more complete set of computable information needed for through-life engineering services.

STEP AP 242 contains lot more capabilities than outlined above. It is important to emphasize that the capabilities described thus far are being implemented and tested in major CAD/CAM systems. The prospect for their wide-spread industrial adoption appears to be bright.

3.2 Business objects

Most of ISO STEP AP 242 described in Section 3.1 deals with geometry, except for BO Model that deals with metadata associated with parts. Even these 'business object models' are closely tied to the assembly structure in which various parts are positioned spatially. This type of information is authored and stored in Product Data Management (PDM) systems that manage 3D CAD models.

But non-geometric metadata, such as bill of material (BOM), about a product are important for manufacturing and through-life engineering services. The BOMs are managed by Enterprise Resource Planning (ERP) systems and various other engineering information systems, such as Manufacturing Operations Management (MOM) systems and software systems that support maintenance and service. Some of these needs are addressed by Business Object Documents (BODs), which are engineering and business message specifications developed by the Open Application Group Inc. (OAGi) [12]. The entire suite of specifications is called Open Application Group Integration Specification (OAGIS). OAGi has recently released OAGIS Version 10.

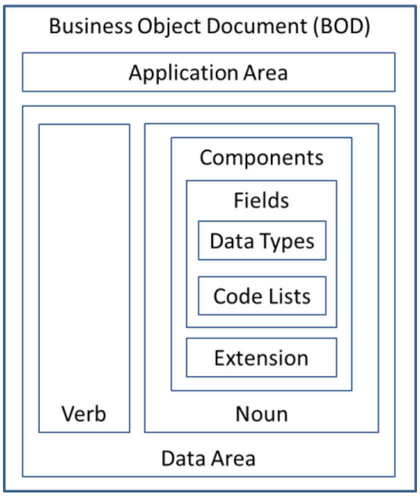

Fig. 3. Business object document (BOD) architecture.

The architecture of BODs is illustrated graphically in Fig 3. A BOD contains two areas: one devoted to application and the other to data. The Application Area contains information needed by the communicating infrastructure to deliver and track the message. It also contains context information that the receiver application may need to process the message correctly. Examples include the engineering or business process it is a part of, and whether it is a production or a test message. The Data Area contains the message content, which comprises Verbs and Nouns. The Verb indicates the action to be performed on the Nouns; the Noun conveys business specific data to be acted upon by the receiver application.

Nouns are made up of reusable elements including Components and Fields. Components convey business data that have a complex structure. They are in turn made up of other Components and Fields. Fields convey business data that have a simple structure; i.e., a single value. Each Field is bound to a Data Type or a Code List that restricts its value domain. An important feature of OAGIS is its extension capability. OAGIS has a built-in extension capability for every component including the application area (which is not illustrated explicitly in Fig. 3).

OAGIS has recently adopted a model-driven approach (MDA), which separates the models from language-specific implementations. Fig 4 illustrates MDA realization in OAGIS 10. The figure shows the packaging structure of OAGIS content. This results in two benefits to OAGIS users. Firstly, OAGIS 10 defines the OAGIS Model, which is then derived into three OAGIS Expressions that are optimized for various deployment environments. For example, OAGIS JSON (JavaScript Object Notation) allows light-weight messages optimized for cloud and mobile deployments. This is an important development because till recently OAGIS focused exclusively on XML. Secondly, OAGIS Model packages reusable content into the Platform package. The package also includes BODs and Nouns that are agnostic to business and engineering domains. The Platform package allows for more pervasive adoption of OAGIS through other consortia that lead to greater interoperability.

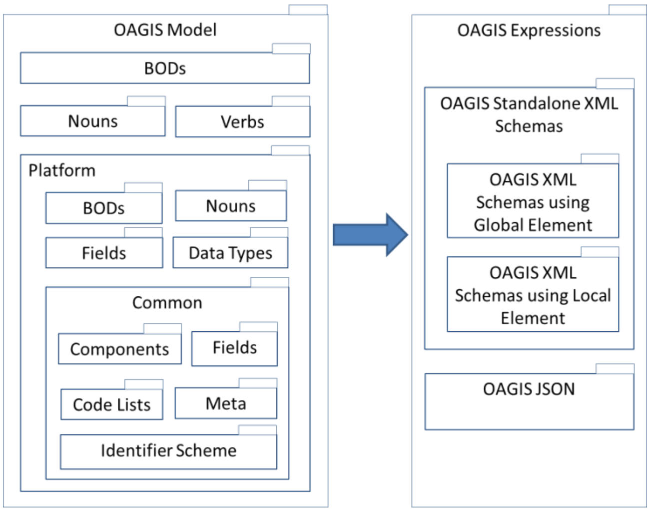

Fig. 4. OAGIS MDA realization and delivery structure.

Although BODs begin with the word ‘business’, they also support transactions in various engineering functional areas throughout a single enterprise or across multiple enterprises. Example transactions include design, manufacturing, supply chain, finance, sales, and accounting. OAGIS support for manufacturing integration is also extended by the Business-to-Manufacturing Markup Language (B2MML) message standard [13] published by MESA International. Recently, OAGi has set up a smart manufacturing working group to push this envelop further; it will investigate how a reference model may be used to improve the reuse of information services relevant to manufacturing. OAGi has also started a semantic refinement working group to improve the precision of OAGIS-based services in declaring their interface capabilities.

The breadth of verbs and nouns coverage, software vendor support, and model-driven approaches have all enabled OAGIS BODs to support composition of engineering services distributed over the cloud. In a recent

OAGIS implementation case study, Fraunhofer Institute has used OAGIS in the cloud computing for logistics [14]. The goal of that case study was to provide a marketplace where users could compose logistics software services using cloud computing to satisfy their business process requirements.

3.3 Model-based systems engineering

Long-lived, complex artifacts are designed, built, and serviced using systems engineering principles. Thus far the requirements, realization, and maintenance of such systems have been managed largely using documents that are only human readable. Model-based systems engineering (MBSE) tries to change this practice by using machine-readable models instead of these traditional rich-text documents [15]. SysML is a standardized systems modeling language to enable MBSE [16].

SysML is an extension of the Unified Modeling Language (UML), which is well-known in software engineering. Fig. 5 shows the relationship between UML and SysML using a simple Venn diagram. SysML defines additional diagrams, which are not contained in UML. These diagrams capture requirements and parameters that enable engineers to represent complex requirements, and to link them to systems simulation and analysis programs such as SIMULINK and MODELICA. SysML Version 1.3, which was released recently, has been implemented by several leading systems engineering software vendors.

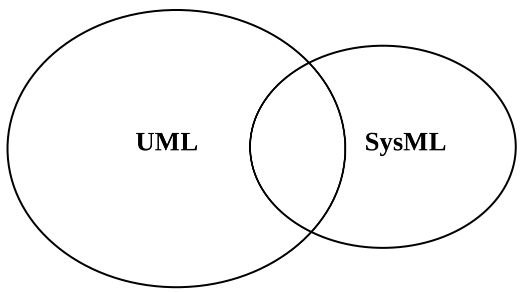

Fig. 5. Relationship between UML and SysML

SysML is closely related to ISO STEP AP 233 [17], which deals with systems engineering. ISO STEP AP 233, in turn, has several common features with ISO STEP AP 239 [18] that deals with product life-cycle support, which is of considerable interest to through-life engineering services. Therefore, we turn to that next.

3.4 Product lifecycle support

Product LifeCycle Support (PLCS) [19] is the domain of ISO STEP AP 239. At the minimum, PLCS provides standardized representations for product configurations during various phases of a product lifecycle (e.g., as-designed, as-built, and as-maintained). But, it provides much more. PLCS also deals with in-service support requirements (hence the connection to model-based systems engineering in Section 3.3), and related resources such as maintenance plans, schedules, job cards, and work request/orders. In fact, recent versions of PLCS are defined using UML/SysML.

The relationship between STEP AP 233 (Systems Engineering) and PLCS is shown in Fig. 6, where some of the functionalities of these two standards are also outlined. It is clear that these two standards share considerable capabilities.

PLCS has found strong support in the defense sector, where sustainment of weapon systems is paramount. Several pilot implementations of PLCS by major defense contractors are underway [20]. But the capabilities of PLCS extend far beyond defense applications. Section 5 outlines a scenario in a generic manufacturing plant floor (i.e., not restricted to the defense sector) that can benefit from the PLCS capabilities.

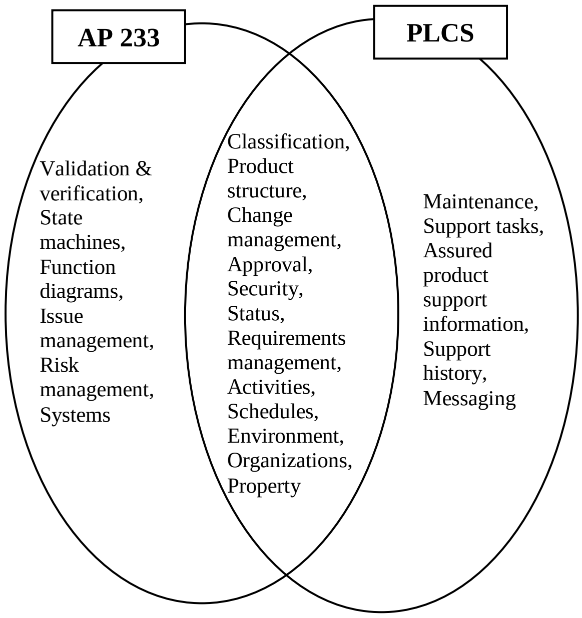

Fig. 6. Relationship between ISO STEP AP 233 and PLCS

3.5 MTConnect

Smart manufacturing systems need smart machines and devices. However, machines and devices are typically designed to function independently with limited intelligence. Consequently, coordinated intelligence is even more difficult. MTConnect is an open standard [21] to enable intelligence to be built on top of existing machines. Applications of MTConnect have enabled more efficient manufacturing production and through-life engineering processes by providing interoperable machine data to intelligent applications.

MTConnect is developed by the MTConnect Institute for networking manufacturing devices and applications. It allows device data including subcomponents, measurements, and events to be uniformly communicated to applications such as Manufacturing Operation Management (MOM), Performance Diagnosis and Prognosis (PDP), and predictive (e.g., condition-based) maintenance. MTConnect standard is relatively easy to use because it relies on the popular HyperText Transfer Protocol (HTTP) and XML standards to deliver data.

Fig. 7a shows the types of data that may be provided by an *MTConnect* device. Fig. 7b shows a hierarchical machine structure and available data (in DataItem); the Component and DataItem can be cascaded into multiple levels in a hierarchy as necessary. The DataItem specifically describes the Streams (in Fig. 7a) available to the client. The Streams is a set of Samples, Events, or Condition for components or devices.

The Samples are measurement values (e.g., temperature, spindle position) at a time point determined by a measurement frequency. The Events are discrete changes in a device's state, while the Condition indicates health and ability of a device to function such as Normal, Warning, Fault, or Unavailable. Multiple Faults and Warnings may be reported for a single data item while only a single value can be reported for Samples and Events. Assets are mobile equipment that can be moved from one device to another such as cutting tools and fixtures.

MTConnect defines four services for clients to retrieve the data: probe, current, sample, and asset. The 'probe' service provides the Devices data. The 'current' and 'sample' services provide the most recent read and a time-window-based Streams data, respectively. The 'asset' service provides Assets data. As new versions of MTConnect are developed, more components, data items, and assets can be added to the standard.

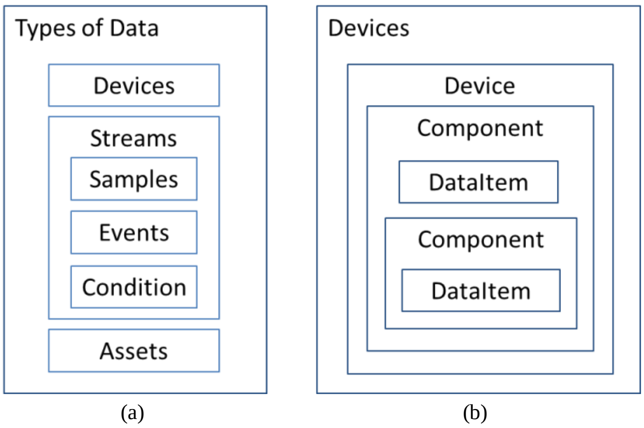

Fig. 7. (a) Types of data in MT Connect; (b) Device data structure

4. Service-oriented architecture

Standards, such as those described in Section 3 and others, have been useful in enabling interoperability among disparate engineering software systems. But the trend is to regard the functionalities provided by these software systems as services. This trend has accelerated recently with the arrival of cloud computing, which virtualizes computing and communication resources.

Service-oriented architecture (SOA) aims to achieve a distributed, loosely-coupled environment such as a cloud-based offering of software components. In the service-oriented paradigm, software components are viewed as providing functionalities through services that are independently owned. Services are virtualizations of software components. That is, service consumers do not need to know how service providers offer their services – from where, by which, or by how many software components.

The service-oriented paradigm emphasizes visibility and semantics that enable (1) the matching between needs and capabilities, and (2) the composition of capabilities to address those needs. The visibility and semantics are enabled by service descriptions and service contracts that capture the essential information the service consumers and providers need to be aware of and agree upon.

SOA is commonly implemented using Web Services, which refer to a suite of standards from multiple standard development organizations; these standards include Web Service Description Language (WSDL) [22] and Business Process Execution Language (BPEL) [23]. However, such services may also be implemented using other strategies. Recently, SOA implementation using Representational State Transfer (REST), also known as RESTful Web Services, has gained widespread acceptance [24]. The RESTful implementation is regarded as simpler and easier to use than the WSDL-based counterpart.

Although SOA provides the paradigm and necessary technology to enable dynamic composition of engineering information services, it is not itself a solution to domain-specific problems. The following section describes a through-life engineering service scenario to illustrate how several engineering information services can be composed using SOA to provide a domain-specific solution.

5. Composing services

Any engineering information system can provide a service. An important question we should ask is whether such services can be composed to provide a bigger service that matters to a customer. In addition, we should ask how quickly such a composition can be put together or modified in a dynamic industrial and business environment. The best way to answer these questions is (1) to gather realistic scenarios from customers for existing or anticipated problems, and (2) to test the hypothesis of dynamic service composition on these scenarios through experimentations with service-based solutions. Consider the following scenario that describes a service call affecting a production line in a manufacturing plant [25-27]:

"A fault from an Electrical Control Unit (ECU) for the motors powering the plant's central conveyor line is detected by a Performance Diagnosis and Prognosis (PDP) system, which monitors and brokers all critical plant equipment over the plant's wireless local area network (WLAN). An 'event' notice is instantly dispatched to a

Manufacturing Operations Management (MOM) system, where an operations manager uses a Decision Support system to determine if the fault is a false alarm, a new alarm, or a recurring problem. The motor's calibration and instrument reading, also monitored by PDP and SCADA (Supervisory Control And Data Acquisition) systems via the WLAN, confirms that the fault is real. PDP has compared the ECU's signal history with the manufacturer's specifications; and, while it remained within performance limits, it is likely to fail soon.

"Plant operators issue a high-priority work order through MOM, alerting an on-duty field technician to the problem via a Smart Phone message. The technician uses his (mobile) tablet to review the work order, identify the ECU's unit number, physical location, safety notifications and a brief description of the fault type.

"MOM automatically prepares an audit report of the ECU's previous maintenance and performance. MOM determines from its ERP (Enterprise Resource Planning) system interface that there is no warehoused replacement ECU. However, a direct query of the ECU manufacturer finds another vendor's part is equivalent. There also is a field performance upgrade that improves the current ECU's operational characteristics.

"Meanwhile, the technician locates the faulting ECU and takes the motor off-line by locking out its power system, a standard safety procedure appearing in his tablet's checklist. The technician also uses his tablet to access the vendor's PLM (Product Lifecycle Management) system to retrieve design specification, installation, configuration, and testing procedures. He notices an optional, performance-enhancement service bulletin and compares output signals with the failing ECU. After consulting with Operations, he applies the optional upgrade to bring the conveyor motor back into a no-fault operating condition.

"The technician downloads the performance package to the ECU along with the vendor's recommended testing and startup procedures. The installation and pretest are quickly completed. He refers to the standard restart procedures and brings the conveyor back on line. Then the ECU is monitored locally to insure that the startup sequence has not stressed the ECU or motor beyond performance standards.

"The technician uploads the ECU's operational history and diagnostic outputs at the time of the fault. The ECU's manufacturer will investigate the circumstances to determine if there is a fundamental design flaw. The service request is closed out and standard operations resume."

The scenario described above illustrates several key ideas. Humans play important supervisory and collaborative roles; but, humans should not be required to reenter information that already resides in a trusted source. Also, humans should not be required to read and interpret textual or graphical information. That information should be represented in a machine-readable form that can be interpreted quickly and correctly by a computer. These are some of the key elements of smart manufacturing. In a realization of smart manufacturing, the reader can envision the automation of several processes that are manually carried out in the scenario outlined above.

Implementing even this relatively simple scenario as a valuable composite process involves several engineering information systems whose services need to be composed. It is highly unlikely that one single software vendor or organization will be able to provide all the engineering information systems, and integrate those using proprietary data and interfaces.

The trend is to use standardized data, such as those described in Section 3, and standardized service interfaces using SOA as described in Section 4. As the scenario indicates, such data can come from different PLM, ERP, MOM, and SCADA systems. Considerable data analytics are also employed to monitor equipment health, diagnose problems, and suggest corrective actions. These data and systems are now moving to clouds, and the scenarios are changing fast to reflect demanding business needs. Hence, we face the urgent need for dynamically composing these engineering information services in the cloud.

6. Summary and concluding remarks

In the current era of digitization of manufacturing, also known as smart manufacturing, engineering information systems play a central role. No single software vendor or organization can provide all the necessary software and services. Therefore, proprietary data and interfaces are no longer a viable option to serve the lifecycle and supply networks of complex, long-lived products. Hence, standards have assumed an important role.

In this paper, we described some of the standards that have been created or upgraded recently to meet the demands of smart manufacturing. These standards are based on information models with semantic representations that are machine readable. By avoiding human interpretations and interventions as much as possible, costly and time-consuming errors can be avoided.

With the aid of service-oriented architecture, these standards also enable composition of engineering information services to meet more complex and fast changing engineering and business needs. We have already seen some success in deploying such services in industry; but, many challenges remain before we can realize the full potential.

Cloud-based engineering information services are still in their infancy. Breaking the proprietary hold on data and interfaces still remains a problem in manufacturing. As open standards for data and interfaces become more popular, innovative entrepreneurs will use them to open up new markets. This is especially important for small and medium sized companies who cannot afford costly solutions. We need more software technologies and tools to define and compose the engineering information services in manufacturing, which places a higher premium on timeliness and reliability. So, we also need better communication infrastructure (e.g., more deterministic Ethernet), and better cyber security for both wired and wireless communication.

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References

[1] McMahon C, Ball A. 2013. Information systems challenges for through-life engineering. 2nd International through-life engineering services conference, Procedia CIRP 11, 1-7.
[2] Srinivasan V, Lämmer L, Vettermann S. 2008. On architecting and implementing a product information sharing service. Trans. ASME JCISE, Vol 8.
[3] Srinivasan V. 2011. An integration framework for product lifecycle management. J of CAD, Vol. 43, pp. 464-478.
[4] The Economist. 2012. April 21 issue on the Third Industrial Revolution.
[5] Recommendations for implementing the strategic initiative INDUSTRIE 4.0. 2013. Securing the future of German manufacturing industry. Acatech, Germany.
[6] Rometty V. 2013. The year of the smarter enterprise. The Economist, The world in 2014 edition.
[7] Advanced manufacturing portal. http://manufacturing.gov
[8] STEP AP 242 project. http://www.ap242.org
[9] Barnard Feeney A, Freschette S, Srinivasan V. 2014. A portrait of an ISO STEP tolerancing standard as an enabler of smart manufacturing systems. 13th CIRP Computer Aided Tolerancing Conference, Hangzhou, China.
[10] Long term archival and retrieval. http://www.lotar-international.org
[11] Hunten K, Barnard Feeney A, Srinivasan V. 2013. Recent advances in sharing standardized STEP composite structure design and manufacturing information. J of CAD, Vol. 45, pp. 1215-1221.
[12] Open Applications Group. www.oagi.org
[13] MESA International. Business to Manufacturing Markup Language. www. mesa.org/en/B2MML.asp
[14] Fraunhofer cloud computing for logistics. www.ccl.fraunhofer.de/en.html
[15] Model Based Systems Engineering Wiki. www.incosewiki.org.uk/Model_Based_Systems_Engineering/index.php?title=Main_Page
[16] Systems Modeling Language. www.omgsysml.org
[17] ISO 10303-233: 2012. Industrial automation systems and integration – Product data representatin and exchange – Part 233: Application protocol: Systems engineering, Geneva, Switzerland.
[18] ISO 10303-239: 2012. Industrial automation systems and integration – Product data representation and exchange – Part 239: Application protocol: Product life cycle support, Geneva, Switzewrland.
[19] Product life cycle support. plcs-resources.org
[20] UK MOD and PLCS. www.eurostep.com/news/plcs-implementation-made-easier-by-uk-mod-sponsored-project.aspx
[21] MTConnect standard version 1.2.0. www.mtconnect.org/getting-started/developers/standards.aspx
[22] Web Services Description Language. www.w3.org/TR/wsdl20-primer
[23] Business Process Execution Language. docs.oasis-open.org/wsbpel/2.0/Primer/wsbpel-v2.0-Primer.html
[24] Representaional State Transfer Web Services: The basics. www.ibm.com/developerworks/webservices/library/ws-restful
[25] Srinivasan V. 2009. Sustaining manufacturing assets through smarter utilization of information and communication technologies. 5th Annual IEEE Conference on Automation Science and Engineering, Bangalore, India, Aug. 22-25. Pp. 478-482.
[26] Popko E, Luyer E. 2009. Asset management to support product lifecycle management (PLM) – leveraging asset management to benefit PLM projects. IBM White paper.
[27] Ouertani ZM, Srinivasan V, Parlikad AK, Luyer E and McFarlane D. 2009. Through-life active asset configuration management. 6th International Conference on Product Lifecycle Management, University of Bath, Bath, U.K.