Empowering Industrial Maintenance Personnel with Situationally Relevant Information using Semantics and Context Reasoning

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Abstract: Industrial maintenance is a complex discipline requiring experience and know-how. Information such as maintenance work orders are usually provided through mobile devices to field personnel. There are also other information sources with manuals, documented history, contact information etc. that is of value supporting the tasks at hand but typically this needs to be retrieved manually. The challenge is how to utilize information originating from heterogeneous information sources that, in addition, may change e.g. for outsourced maintenance service providers taking care of different sites. To facilitate the use of supporting materials an ontology knowledge management approach is developed that integrates data and documents, and provides relevant information for the task at hand using context and semantics based reasoning. Results from early prototyping show that the approach can improve utilization of information in existing systems through adapter layers and complement existing mobile as well as upcoming augmented reality applications by automatically providing situationally relevant information.

1 INTRODUCTION

In industrial production environments the availability of equipment and machines is critical to the efficiency of production. Maintenance is a key factor in this for achieving high reliability and required precision of operation. As a discipline maintenance is knowledge-intensive and requires expertise in executing demanding tasks of servicing machines and equipment.

In their work maintenance technicians follow tasks assigned to them using work orders. Although this information is in digital form there are seldom accessible paths to other information that would be of use to support the task at hand. Such supporting information is, for example, service manuals, operating instructions, and documentation from similar previous tasks. This is partly due to the heterogeneous nature of those information sources. Even though this information would exist it is not always easy to find and productive time may be lost.

The challenges, and associated costs, are becoming more evident with outsourced maintenance services putting a price tag on individual maintenance tasks. Having access to relevant information is also a challenge for typical service providers having multiple sites at their responsibility (Murthy et al., 2015), e.g. with differing practices as well as different information systems. This is not only a problem of inexperienced personnel but also for experienced personnel that need to handle a broader range of tasks. It can be claimed that information is not exchanged as it was before and that especially the transfer of tacit knowledge can be reduced due to this model of operation.

The paper presents research how industrial field service personnel (FSP), i.e. maintenance technicians, can be supported with situationally relevant information. The aim is to develop an integration platform that using semantics based reasoning combines and makes better use of existing information. In this paper the focus is on conceptualizing the knowledge management solution, defining a system architecture and evaluating implementation technologies.

The paper is structured as follows. Section 2 provides an overview of background information and related work. Section 3 outlines characteristics and current challenges based on interviews and discussions with companies. Based on this, in section 4, a concept is developed what kind of information is provided and from which systems. In section 5 the use of Semantic Web technologies is discussed to manage different

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data sources with information related to the maintenance. In the approach Semantic Web technologies are used to classify content, adapt different metadata, and to reason and combine knowledge with regard to the current context of the maintenance technician. Discussion is provided in section 6 before concluding the paper with future work in section 7.

2 RELATED WORK AND BACKGROUND

2.1 E-maintenance

During the last decade the working environment of maintenance technicians has developed rapidly along with ICT technology evolution. Especially, the Internet, new web technologies and wireless networks have enabled this development to a new level often called as e-maintenance. E-maintenance is defined in (Campos et al., 2009) as the ability to monitor plant floor assets, link the production and maintenance operation systems, collect feedback from remote customer sites, and integrate its upper level enterprise applications. The most preferred e-maintenance strategy is condition based maintenance (CBM), which can be advanced by the introduction of new technology.

These new technologies have changed the way how maintenance functions are carried out and provide new tools and access interfaces for FSPs. They have enhanced data collection (e.g. Radio-frequency identification (RFID) & smart tags, micro sensors) and data analysis functions implemented as web services. Wireless networks enable mobile communication with advanced interfaces and computation power (smartphones, tablets). For instance, RFID smart tags enable fast identification of machines using mobile devices and easy access to maintenance related data stored in them, such as, location, spare parts, tools and even information about the past maintenance actions. The e-maintenance concept address also the requirement of enhanced system interoperability and information integration by widely accepted data model standards, such as, Mimosa (Machinery Information Management Open System Alliance) OSA-CBM (Open System Architecture for Condition Based Maintenance)(MIMOSA, 2010) and ISA-95 (IEC, 2013). (Holmberg et al., 2010)

Many of these new technologies have already mature deployments and are in daily use by maintenance technicians. In a near future, maintenance systems are expected to enable more intelligent use of collected data from remote distributed sources through sensor hubs and cloud computing; wearable computing and augmented reality (AR) services will enable to relay detailed guidance to inexperienced maintenance technicians at remote sites. (Holmberg et al., 2010)

Many challenges are still related to information integration and knowledge management in the maintenance domain (Ruiz et al., 2013). Semantic Web technologies, as seen for e-maintenance, are enabling technologies that can provide new solutions also for this area. For example, they enable flexible and expressive knowledge representation by ontology models, advanced search capabilities, information integration at semantic level, ontology and rule based reasoning capabilities, etc. Semantic Web technology standards managed by W3C are an important set of complementary standards for e-maintenance.

2.2 Contextual Computing

The fast development of mobile and sensor technologies has enabled implementing smart mobile platforms with enough computing power for context-aware applications. Its importance in providing intelligence to new applications will grow in the future together with other technologies supporting the Internet of Things (IoT) and Services (IoTS) paradigms.

Recent survey papers about context-aware computing are (Perera et al., 2014; Hong et al., 2009). The notion of context in general has been studied in (Dey, 2001; Abowd and Mynatt, 2000). Definition of the concept has been further refined and categorization of context-aware computing provided in (Soylu et al., 2009). Review and categorization of contextual reasoning and modeling approaches have been presented in (Perera et al., 2014; Nalepa and Bobek, 2014).

Generic context models and ontologies have been developed in (Soylu et al., 2009; Wang et al., 2012; Gundersen, 2014; Wang et al., 2004; Chen et al., 2005; Mettouris and Papadopoulos, 2013). A practical design and implementation of a rule-based context-aware system for health care domain is presented in (Wang et al., 2012).

Examples of industrial applications of contextual computing are (Gundersen, 2014; Pistofidis et al., 2014; Zhu et al., 2015). (Gundersen, 2014) apply contextual computing in a situation assessment process for oil well drilling operations. (Pistofidis et al., 2014) define a model for failure context to support diagnostic and maintenance services. The generic context ontology defined in (Wang et al., 2004) has been extended in (Zhu et al., 2015) to support AR assisted maintenance systems.

2.3 Industrial Semantic Web

A semantic data integration system has been studied by (Kunz et al., 2010) focusing on data federation to enable IoTS. For operational decision making and run-time data acquisition an ontological framework has been developed by (Muñoz et al., 2012). In another approach to increase interoperability of dynamic manufacturing networks an interoperability framework has been presented (Figay et al., 2012). To improve use of engineering information and interoperability an approach based on ontologies has been proposed in a model-driven development context (Chungoora et al., 2013). These, however, do not target needs presented in this paper but due to a similar basis they provide efficient means for connecting such information to the approach of this paper.

3 INFORMATION EXCHANGE CHALLENGES

Maintenance in production environments can be carried out based on a number of strategies but the maintenance intervals and practices applied depend, among other factors, on the target, its role and criticality in the system, and the expertise and know-how required. Maintenance may also include remote work but remote monitoring is not in the scope of this paper.

The challenges discussed are based on feedback and discussions with industry professionals. Themed free-form questionnaires were sent out to a small number of chosen industry professionals. Additionally, also observations were made during workshops discussing these and related topics.

3.1 Fragmented into Different Systems

A large number of information systems are used in industrial operations, especially in large production environments. The following information systems can be identified of importance to maintenance activities:

- Plant or device model information systems: Plant or device asset data stored typically as a logical hierarchical structure including attributes and characteristics. Usually the result of the engineering phase and its master data is often stored in enterprise resource planning (ERP) level systems.
- Maintenance information systems: Data related to active maintenance tasks, previously performed maintenance actions and service history which accumulate during the lifecycle for e.g. a production facility or an individual device.
- Condition monitoring systems: Data representing the health and operational conditions of individual devices and assets actively monitored e.g. by dedicated measurements. These systems are often third-party provided and device specific. Aggregating condition monitoring systems are also used especially for communicating alarm event information to human machine interfaces (HMI).
- Control systems: Control systems operate a wide range of devices and equipment in the daily production. Complex distributed control systems (DCS) often include advanced monitoring features as well as information on operation status that reflect the current state of the machinery.
- Device catalogs and supporting documents: Device vendors and equipment manufacturers typically provide datasheets, manuals and other supporting instructions for their devices through dedicated portals or in-house support channels.

A key issue for maintenance services is that a significant amount of this information is linked and required for assessing and performing the required maintenance activities efficiently. In a typical scenario the FSP use information of assets to be maintained from the plant model information system, e.g. the exact location identifier for the correct target as well as for accounting the related costs. The decision whether to do a maintenance action, on the other hand, can be based on a periodic schedule in the maintenance information system or by some degraded condition indicated by a condition monitoring system. Similarly the control system can provide such information with alarms as well as the status of the machinery to decide whether the maintenance task can be carried out safely. To perform the maintenance task the person might need device specific supporting documents and manuals.

Most of this information is available but retrieved manually and communicated by emails and direct conversation. This consumes valuable time as well as hinders the full utilization of information. In manual or poorly integrated systems it is not uncommon that some other maintenance task escapes one's attention that could have easily been performed at the same time. This is obviously costly when downtime is increased when maintenance efforts are not optimised.

The aforementioned systems are often heterogeneous facing the typical integration challenges for building effective solutions. This means that apart from the different types of communication protocols also the information semantics vary.

3.2 Information Management

In production environments it can be argued that asset information becomes over time more important than the physical asset itself. An example of this is maintenance history that is critical for the overall operation of some machinery. Having a spare device does not help if production is unexpectedly stopped resulting in lost production easily exceeding the monetary value of the failing device. Maintenance affects the OEE indicator (Overall Equipment Efficiency = Availability x Performance Efficiency x Rate of Quality) especially through availability and quality.

Management of information in industrial production facilities is challenging also due to the large number of devices and equipment installed. A processing facility, for example, can contain hundreds or up to thousands of devices that depending on the manufacturer have their information and attributes differently in the plant model information system. Fortunately for industrial informatics there are several standards that facilitate the communication such as Mimosa for maintenance activities, ISA-88 and ISO 15926 for production equipment structuring and attributes, and ISA-95 for manufacturing to enterprise communication, to name a few of the applicable standards that can be used to harmonize information management.

A CBM system increases the knowledge of the risk of failure, and is therefore an important means to maximise availability and effective hours of critical components. Typically these systems continuously monitor the asset of interest and based on data-analysis from a larger set of similar devices some threshold values can be detected when maintenance should be performed. The know-how to interpret these signals, e.g. deviations in vibration analysis results, switching times for internal components etc., is often the expertise of the device manufacturer. It is often provided as an additional billable service to the operator or owner. From the operator perspective the raw data is not of core interest, i.e. only the performance indicators, while the manufacturer on the other hand may depend on this for doing analysis on a larger set of devices. Depending on the implementation this information can be provided directly from the device or as a remote service e.g. over the Internet.

A mobile remote asset, such as a crane or some other movable device, is not similarly part of any factory network. In such cases status and condition data is often gathered from the device to a cloud storage, either automatically on-line or periodically between stationings or when visited by a maintenance technician. For modern devices this can be provided remotely to the site over the Internet but for many older systems this is a combination of Internet retrieved data, e.g. maintenance history, and local information on most recent condition developments and events.

3.3 External Service Providers

The business models have also changed and many production facility owners, or operators, focus on their core tasks. As a result, maintenance is often outsourced to various service providers, e.g. generic routine maintenance and highly specialised services.

In all cases the external service provider needs information from the various information systems previously listed. To some extent this can be reduced with planning from the operator side and a direct link to the plant information model system can be eliminated, i.e. that being an ERP system in many cases. The rest of the demands, however, remain. From the service provider side the challenge and associated system integration cost is even greater as the same service provider may have liabilities with several customers, i.e. several different production facilities.

A maintenance service person needs to have access to the assigned task but also to information on previous maintenance history. An experienced FSP can, for instance, spot on-site a cause to some recurring failure with knowledge of previous incidents. Outsourced personnel do not necessarily possess the experience from working with the equipment for years or the practices and methods previously applied. Supporting documents and guidelines become important in these cases and they need to be communicated efficiently while the task is at hand.

Sometimes demanding maintenance service work is performed by relatively inexperienced persons such as the machine operator. In such cases the guidelines need to be explicitly provided as the person may have no idea where to search for such information in the first place. However, in such cases remote monitoring and assistance can also be used to support the work.

3.4 Tacit Knowledge in Maintenance

An important factor in maintenance work is the use of tacit knowledge, i.e. the experience and non-explicit know-how. An experienced FSP knows how to troubleshoot failures efficiently, what information is needed to perform the work and where to find it, how to proceed with the maintenance action such as a replacement, and what information in the work report might benefit similar cases in the future. This can be assisted with guidelines but creating such for diverse tasks is laborious on its own. General challenges with tacit knowledge is first of all identifying it and secondly explicating it so it can be used in the future.

Lack of knowledge and routines is, however, not only a case for inexperienced maintenance technicians. Especially with outsourced maintenance services the tasks are circulated among a larger number of persons and these persons often also have maintenance tasks at different locations. This hinders building up routines as well as communication and information exchange that e.g. used to take place sporadically. For equipment that are for instance rented or moved to remote locations it might also be that a non-professional needs to do basic maintenance tasks (e.g. lubing). An extreme real-world case requirement can be that such guidance needs to be visual.

Assisting video material could be used to illustrate work tasks and in the future AR could significantly help performing maintenance with augmented instructions and object highlighting either using a mobile device or wearable AR glasses. With advances in AR technology user actions could even be captured and identified semi-automatically. This could be used for example to capture tacit knowledge of experienced persons without interfering with their work. Secondly, it could automatically allow extracting information on completed operations that in addition with the known work task context could be used to assist in reporting. The latter could help with sometimes encountered reluctance of writing reports.

Tacit knowledge as such is considered to be out of the scope of this paper. However, utilization of explicated tacit knowledge is considered a requirement. For example, video material that is currently already used could easily be provided as support to the maintenance task at hand given that metadata is available.

3.5 Summary of Requirements

The previously listed challenges can be transformed into the following requirements. Based on constructive research of design science methodology (Crnkovic, 2010) they are projected into models and software constructs as building blocks which enable testing the theories and examining the new reality.

- The information provision solution needs to support gathering and integrating information from several different sources with varying content.
- Standard based definitions should be used for organizing maintenance related information in order to improve further knowledge utilization.
- The solutions should allow the use of adapters to reuse once implemented adaptation for similar information types and enable classification based on standard concepts.
- Reasoning needs to be supported to provide the relevant supporting information with minimal user effort.
- The context information should be reused to assist and simplify reporting but also to store situational information for future analysis and support improvements.

4 EMPOWERING TECHNICIANS WITH SITUATIONALLY RELEVANT INFORMATION

Providing required and supporting information relevant to the maintenance task, either automatically or semi-automatically, enables the FSP to focus efforts on the actual value-adding work and improves confidence in performing the task. Accessing supporting documents, manuals, previous maintenance history and other information is still highly dependent on preparatory work that can not always be foreseen.

4.1 Architecture Overview

Figure 1 presents an overview of the concept how and what kind of information is provided to the maintenance technician. The lower section of the figure illustrates information such as guidelines and instructions of the maintenance service company, manuals and other documents provided e.g. by device vendors, and information originating from data repositories as a result of data analysis. On the bottom left of the figure the information sources originating from the site of maintenance are depicted. These include control systems providing runtime information but also ERP as well as MES (Maintenance Execution System) level information is typically required. The latter sources typically contain site specific information e.g. on production operations but also in-house inventories of spare parts, replacements etc.

For software applications to be able to use provided information efficiently metadata is required both for interfaces as well as the data content. Especially in cases where information sources and the content structure change a knowledge management solution is required. This is where the semantic interface gateway, referred to as the Knowledge Gateway (KG), acts as a key enabler in mediation. It provides a uniform point of access to heterogeneous sources that based on metadata allows for reasoning what is relevant in different situations the maintenance technician encounters.

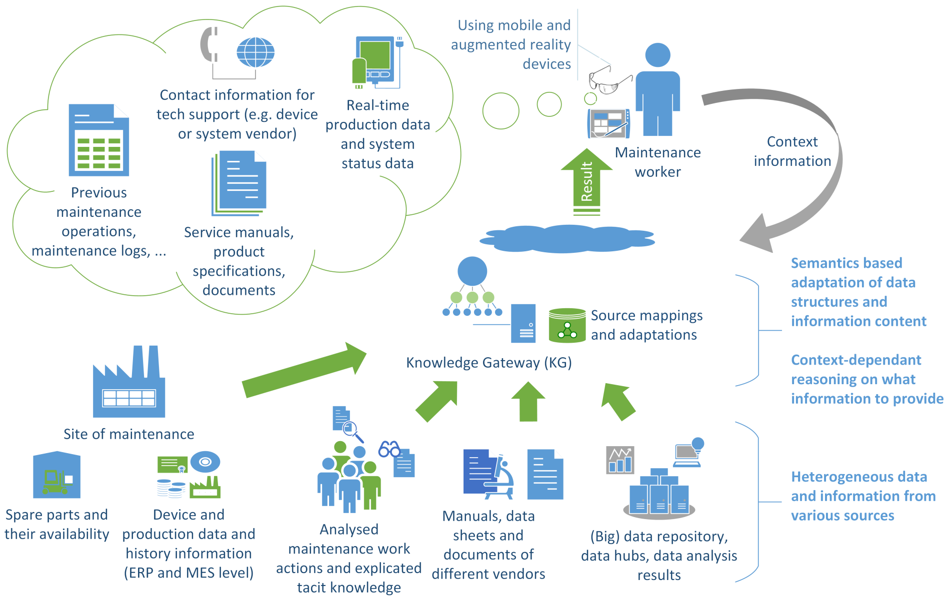

Figure 1: The maintenance knowledge management concept is based on a knowledge gateway (KG) that combines information from various sources in a meaningful way based on semantic descriptions and reasoning of the context.

4.2 Linking Information Sources

To achieve its goal the KG requires a basic model for understanding the operational context as well as what each information source and slice of data represent. This along with mappings, and adapter layers to proprietary systems, allows contextual reasoning to provide the relevant information to the maintenance task.

For static documents there are description methods and similar models are also emerging for AR and other multimodal media material (Olmedo, 2013). Also runtime information systems support several sophisticated means for providing operational data. An example of this is OPC UA (Open Platform Communications Unified Architecture) (OPC Foundation, 2009) that in addition to an acknowledged standard protocol for accessing diverse systems also offers information modeling features e.g. for describing semantics to be used in dynamic discovery.

In the concept a mobile device can automatically provide information on previous maintenance operations, manuals, system status as well as contact information for key persons in contrast to manual searching from diverse sources. The context allows linking the task with the targeted machine to access e.g. supporting documents originating from the vendor. Similarly the identified machine can be used to retrieve previous maintenance history of e.g. same type of actions. Using the facility segment location other open tasks can be automatically shown in case they can be performed during the same stop in production.

4.3 Maintenance Technician's Context

The meaning of context notion is difficult to capture because of its open nature. For instance, some particular knowledge is considered to be part of context in one setting while it is not in another setting. A general definition often cited in literature has been presented in (Dey, 2001): "Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves." Accordingly, context is information about some situation. Defining situation as a state of an entity and its environment implies that information about an environment is also an essential part of context.

In this study, the scope of the context needs to be defined for the maintenance application domain. the basic concepts and high level context categorization are based on the Situation Assessment Context (SAC) model defined in (Gundersen, 2014). In this model situation is defined as a static state of an entity and its environment. Events can change this state creating a new situation. The state can be described by information elements relevant for the situation. Consequently, situation is defined by the context elements forming or characterizing the situation and element relations.

The SAC hierarchy is extended and specialized for maintenance operations domain by ten new categories represented in figure 2 as Maintenance Context (MC)

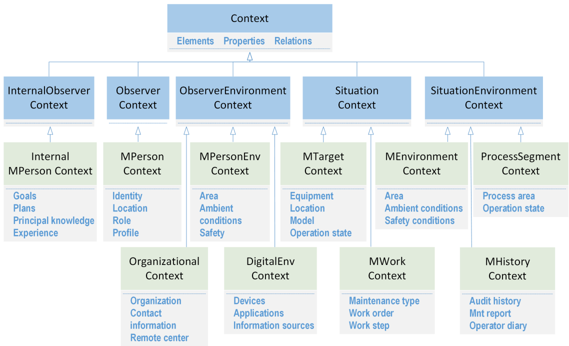

Figure 2: A class diagram presenting MaintenanceContext classes (two lower rows) in SituationAssessment context hierarchy (two upper rows). Some examples of the possible Elements of the Context classes are listed as class members.

classes. As a result, the overall operational context model consists of ten contexts with different sets of elements which represent different aspects of the total knowledge content.

In the MC model, a maintenance person (MPerson) represents the Observer of the SA model. MPerson's maintenance work (MWork) is related to some target machine (MTarget) which can be part of some larger production segment (ProcessSegment) in a production area. Maintenance work can consist of several work steps and sub operations. After finishing one work step and changing to the next one, the situation of the maintenance technician might also change especially if the next task need to be done in a new environment location. In fact, the situation dynamics is mainly related to the dynamics of the workflow and the accuracy it is observed and recorded.

In addition to ProcessSegment context there are two other dimensions of the target environment (SituationEnvironment) that need to be described in the model. MEnvironment contains elements with information about the conditions in the maintenance area that can affect work preparations and execution. MHistory context will provide information about the maintenance history of the target, such as links to the latest maintenance reports.

ObserverEnvironment context is described by three more specific sub contexts. First, MPersonEnvironment context contains by default the same information as MEnvironment. However, there are situations when the environment of the maintenance worker is different from that of the maintenance target. Second, Organizational context provides information about the maintenance organization and people, e.g. the contact information of experienced maintenance people at the site and remote support center. Third, DigitalEnvironment context contains the listing of available applications and data sources that can be accessed for support information.

5 KNOWLEDGE MANAGEMENT BASED ON SEMANTICS

The previous section introduced the concept of providing situationally relevant information for the maintenance technician based on the context to support the task at hand. As discussed in section 3, integrating such information is challenging especially with changing maintenance locations and varying back office information systems. For this the use of information semantics is proposed to assist in the meaningful interpretation and combination of knowledge.

5.1 Semantic Web Technologies

For the Semantic Web ontologies form the basis of knowledge with descriptions expressing relationships between objects as well as their properties. RDF (Resource Description Framework) and OWL (Web Ontology Languages), that is built on top of RDF, are commonly used W3C specifications. These ontology concepts, i.e. classes, their instances and property types, are denoted by unique URIs allowing sharing and reuse of concepts. Using a triple statement mechanism relationships are then described between concepts to form the knowledge representation.

More general ontologies, often denoted as core ontologies, are used to map and link concepts in different application specific ontologies. RDF and OWL, in comparison to XML, provide computer interpretable semantics. This means that using reasoning statements and rules new knowledge can be automatically inferred. As a result, and in combination with ontology mappings, this also enables meaningful interpretation of previously unencountered content.

A limiting factor in Semantic Web applications is the open world assumption (OWA) meaning that if something is not stated it does not mean it does not exist (e.g. in the real world). It is simply unknown. This means that the lack of some declaration cannot be used to infer something opposite. In applications with known boundaries, e.g. application specific implementations, techniques such as SPIN (SPARQL Inference Notation) can be used to query and infer on a closed world assumption (CWA). This also means that SPARQL and SPIN can be used for validation of data in comparison to standard OWL reasoning.

Ontology reasoning, especially using OWL in its full extent, is computationally complex. Applications utilizing SWRL (Semantic Web Rule Language) rules, for example, are often of exponential space time complexity. This matters especially in settings combining vast amounts of data. Further on, a topic of its own is combining ontologies from diverse sources

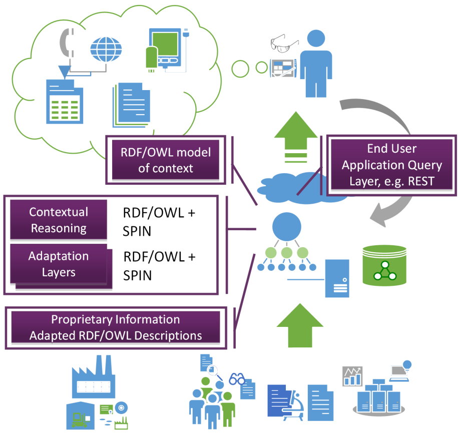

Figure 3: The knowledge management uses Semantic Web technologies for managing information as well as for contextual reasoning to provide content suited the task at hand.

having embedded reasoning axioms unimaginable. In order to overcome this the SPARQL based SPIN mechanism can be used. SPARQL is an ontology query language and SPIN is an application of this for reasoning but also for construction of new knowledge. SPARQL, however, operates on a (RDF) triple level but the triple stores can perform inferences on their own, e.g. using OWL reasoning. SPIN is then used to build layers of queries and construct statements to infer and adapt to different underlying semantics.

Figure 3 illustrates on a generic level the use of the aforementioned Semantic Web technologies in the concept. Unified access to originally heterogeneous data sources is made possible by a semantic repository KB containing all information in RDF graph format. The data access performance of advanced repositories implemented by RDF triple store technology is already well comparable with that of relational databases, which make them a feasible KB solution for the proposed concept (Aarnio et al., 2014).

Adapter solutions are needed to index proprietary content. This is achieved either manually or by tools performing classification resulting in semantically annotated metadata. Considering the current tools available (e.g. as surveyed by (Tosi and Morasca, 2015) and (Madani et al., 2013)) a simple model is considered sufficient. The more advanced adaptation is consider a responsibility of the RDF/OWL and SPIN based adaptation layers. With these layers mappings are developed to general maintenance domain ontology concepts. Using these knowledge constructs reasoning is then performed. To facilitate usability of results a REST interface for simplified access is provided for mobile and other user interface devices.

5.2 Plant and Maintenance Information using Semantic Web Ontologies

To unify the different representations of production facility structures and devices a plant information model has been developed. The ontology model is based on the IEC 62264 (ANSI/ISA-95) standard. It provides a set of concepts for dividing the enterprise environment into hierarchical sites, areas, segments, units and modules. The plant information model provides target locations for maintenance tasks but also serves as the link to surrounding components e.g. in the same segment or unit. Additionally, the plant information model provides information and links to the assets, and further enables linking of additional information of individual devices and equipment.

Furthermore, a lightweight maintenance ontology has been developed as an upper level integration model for potential maintenance related legacy data sources with differing structures. This model is based on well-founded open standard Mimosa's OSA-EAI that covers concept definitions for several maintenance areas including maintenance work orders and activities, asset and segment hierarchies, condition monitoring and diagnostics etc. The maintenance ontology has partially overlapping content with the plant information model, which enables model linking and integrating queries from both models.

5.3 Semantic Representation of the Maintenance Context

The development of the context model ontology was founded on the abstract context modeling principles described in section 4. Design decisions were also constrained by the need to support several functional requirements of the KG system. The final aim is to provide relevant situation dependent support information for a FSP during the maintenance work. Contextual information is exploited in combining, filtering and access of information in the primary knowledge base (KB) as well as providing links to appropriate external services.

5.3.1 Context Model Ontology

The context model ontology consists of two parts: a small set of basic upper level concepts (represented with prefix letter C in figure 4) and an extendable set of domain related concepts defined as specializations of the upper level concepts. The names of the maintenance domain concepts are mostly adopted from Mimosa's OSA-EAI model. The overall operational context model consists of several context instances from different context categories each containing a different set of elements and providing a different view to the primary knowledge in the KB.

Context consists of elements (figure 4) that represent any objects, properties of objects or relations between objects that are considered relevant for the description of a situation. Events that indicate possible situation change are also considered as elements. Elements can be characterized by attributes and associated with binary relations to other elements. Typically, an element should contain information about its type, location and some aspect of time.

Because, the context model is a view model, domain specific elements may have simple data content, but need to have references (URI, ID) to the primary objects in the KB they represent as a kind of proxy objects. This reference value can be used as an argument in a SPARQL query (SPIN template, rule) when a more detailed description of the primary object is required. Furthermore, elements can have references to more than one KB model (named RDF graph) enabling information combination. For instance, the context element Segment may represent a Segment object in the Mimosa model, but also the corresponding Equipment object in the ISA-95 based model, and both models can be accessed through this element.

5.3.2 Contextual Reasoning

Reasoning on the context is carried out mainly at a high conceptual level in the KG. Fast development of intelligent mobile platforms and reasoning engines (Motik et al., 2012) makes it soon possible to do the most low level sensor data based contextual reasoning in real-time already in the user's mobile device. For instance, FSP's movement can be tracked by mobile devices, which can infer his relative location to the target machine and send it as e.g. 'near the target' event message instead of using coordinate values.

Contextual reasoning capability is implemented by SPIN rules. Rules can be embedded to context and element classes enabling object-oriented style of modeling. Four basic kinds of rules are used in the context model: construction rules, information filtering rules, modification rules and constraint rules.

(1) Element construction rules are used to initialize the main attribute values of the created element instances, such as, references to the primary information objects in KB.

(2) Information filtering rules are used to select a relevant set information objects into a solution package to be provided for FSP. What is relevant support information depends on the context, e.g. current work phase and expertise level of FSP.

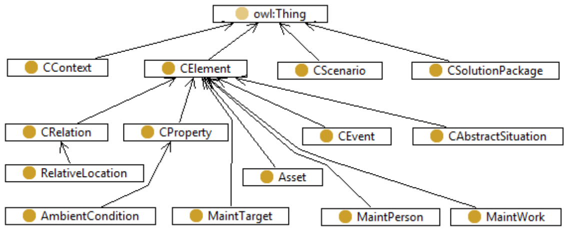

Figure 4: The upper level class hierarchy (prefix C) of the context ontology extended with some of the domain specific CElement subclasses.

(3) Modification rules are used to update element values. Situation rules explained above belong to this category. For example, the following simplified rule representation denotes how a new value of an AbstractSituation element can be inferred and updated depending on the values of other elements:

```
MPerson{relativeLocation('near_target')},
WorkStep{nextActivity('inspection')},
MTarget{Asset{operationState('stopped')}},
WorkStep{permission('granted')}
=>AbstractSituation('inspection_started').
```

(4) Constraint rules can be used to validate element values before other rules are executed, e.g. to check if the state of the target machine is 'stopped' when its service begins and otherwise generate a notification.

The context related support information is provided to FSP as a solution package that is an aggregated package object containing different kinds of guidance information for his work. For example, it can contain the results of contextualized queries, links to maintenance instruction documents and AR-multimedia sources as well as addresses of maintenance service function endpoints.

6 DISCUSSION

The novel solution for integrating maintenance information relevant to the context provides the flexibility required in today's service business environments. The solution allows connecting information from various sources using adapting layers, and based on efficient contextual reasoning automatically provide the relevant information to the FSP. In addition, acknowledged standards are used as a basis for ontology development, thus promoting interoperability and industrial acceptance.

The KG system design based on a semantic KB and RDF data model address the requirements of flexible knowledge representation, easy data model extensions and knowledge sharing. These aspects are highly important especially for contextual modeling.

Since, it might be impossible to predefine the whole context model, it should be easily extendable with new domain specific elements adopted and abstracted from the most essential concepts of the existing primary information models. Further, the approach emphasizes lightweight ontologies defined with limited complexity ontology language (OWL 2 RL) and contextual reasoning by SPIN rules. These design choices enable simple system implementation, when no separate rule-based system is needed. Most of the application logic can be hidden into supple rules and query templates embedded into the ontology allowing execution using standard SPARQL capable engines.

RDF is a metadata language that can be used to represent the semantics of explicated tacit knowledge in a resilient way. At least simple tacit knowledge patterns could be recorded by an easy to use annotation mechanism provided to system users. The idea is that all kinds of user generated annotations, comments and tags can be linked to any elements of a context model and recorded. A set of predefined annotation patterns developed in collaboration with domain experts could improve the usability of this functionality. This functionality justifies the simple and relatively flat structure of the context model, which provides element categorization understandable to the users with basic domain knowledge.

AR-multimedia and videos can be used to record and transmit explicated tacit knowledge of domain experts. Context dependent search of these media requires that metadata describing their content is available in RDF format. In fact, some specifications related to AR-media metadata and search are already under development that can support this search function, such as, ARML and JPSearch. The KG system will provide links to high level situation relevant AR-media and information instances in the solution package delivered to FSP's mobile device. However, real-time contextual reasoning required for presentation of the selected AR-media will be the responsibility of mobile AR applications and reasoners running on FSP's mobile devices (e.g. (Zhu et al., 2015)).

The concept development phase was supported by preliminary evaluation of the main implementation technologies. The basic ontology models were manually developed using an ontology editor. Data access using query templates and contextual reasoning using SPIN rules were tested in an editor supporting SPIN reasoning as well as by using an application developed for this purpose with an open source SPIN API library (Java). Consequently, these technologies were considered feasible for the concept implementation.

7 CONCLUSION

Supporting maintenance technicians with situationally relevant information can improve efficiency and quality of work, and increase general confidence in performing the maintenance tasks. Much of this varying information content is scattered into different information sources. Having information available suited to the task at hand typically requires preparatory work that is away from productive hours, and this is emphasized in the case of external service providers having several facilities to take care of.

The paper first presented requirements for empowering FSPs with situationally relevant information to meet challenges in performing maintenance. Based on these a knowledge management concept was defined including methods for linking maintenance information system data, supporting knowledge, site equipment and other assets. For this a context model was defined so that reasoning could be performed automatically to provide relevant information directly to the maintenance technician. The developed solution is based on using Semantic Web technologies such as RDF, OWL, SPARQL and SPIN to categorize, map, adapt and perform reasoning to flexibly integrate information from diverse sources. As such, the knowledge management approach can improve the utilization of existing data and augments information provided by current mobile applications the maintenance technicians use.

Currently the knowledge management approach and system architecture has been defined, and early prototyping has been performed. In upcoming research, live data sources will be integrated and the adaptation means will be further developed for testing in close to real production environments.

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