A Process Model Discovery Approach for Enabling Model Interoperability in Signal Engineering

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ABSTRACT
In automation systems engineering, signals are considered as common concepts for linking information across different engineering disciplines, such as mechanical, electrical, and software engineering. Signal engineering is facing tough challenges in managing the interoperability of heterogeneous data tools and models of each individual engineering discipline, e.g., to make signal handling consistent, to integrate signals from heterogeneous data models/tools, and to manage the versions of signal changes across engineering disciplines. Currently, signal changes across engineering disciplines are primarily managed manually which is costly and error-prone. The main contribution of this paper is the signal change management process model as an input for semantic integration of engineering tools and models to support (semi) automated signal change management. Major result was that the process model discovery approach well supports the discovery of semantic integration requirements across heterogeneous engineering tools and models more efficient compared to the manual signal change management.

Categories and Subject Descriptors
D.2.9 [Software Engineering]: Management – software configuration management, software process models (e.g., CMM, ISO, PSP).
D.2.12 [Software Engineering]: Interoperability
I.6.5 [Simulation and Modeling]: Model Development – Modeling methodologies.

General Terms
Management, Design.

Keywords
Signal Change Management, Model Interoperability, Automation Systems Engineering.

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1. INTRODUCTION
Complex automation systems, like power plants or car manufacturing workshops, typically involve several different engineering disciplines, e.g., mechanical engineering, electrical engineering, and software engineering that should collaborate to achieve their goals. In such complex automation systems, stakeholders from different engineering fields usually apply individual and discipline-specific tools and models for task execution. Nevertheless, information sharing and collaboration across disciplines and data exchange are pre-conditions for successful project execution. Thus it exists the need for interoperability between different tools and models of such complex automation systems. Currently, a lot of research is done on achieving interoperability between heterogeneous systems and notations [6, 9, 13]. However, most of the approaches are still facing the difficulties involved in overcoming their differences, the lack of consensus on common required standards, and the shortage regarding proper mechanisms and tools [7, 11].

Results of our observation in industry identified signals are common concepts in complex automation systems that link information across different engineering disciplines, e.g., mechanical interfaces, electrical signals (wiring), and software I/O variables. The application field called “Signal engineering” deals with managing signals from different engineering disciplines and is facing some important challenges, e.g., (1) to make signal handling consistent, (2) to integrate signals from heterogeneous data models/tools, and (3) to manage versions of signal changes across engineering disciplines.

To overcome these challenges, one needs to define an interoperability model that illustrates the signal data models and tools from each engineering field as well as their interactions. However, manual design of an interoperability model from different engineering fields is costly and error prone. In the manual model design, all models and required information have to be collected from the domain expert of each engineering fields. Then, the domain expert needs to create the model and its interactions based on the different models collected and cross check with each stakeholder whether the model is correct and the interactions between different engineering fields are correct also. One should do this work and refinement repetitively to obtain conflict-free models. Sometimes, it is quite hard to get a final model that fulfills the requirement from every party, since the requirements themselves could change over the time.

The main contribution of this paper is the proposition of a process model discovery approach to identify the process model for a
exemplary signal change management process and find out the requirements of semantic integration between heterogeneous data models and tools. By using this approach we are able to discover the interoperability model based on the actual data. This model can be useful for illustrating the interactions between engineering fields and detecting the needs of semantic integration in the signal change management. Major results show that by using the process model discovery approach, the requirements of semantic integration across heterogeneous tools and data models from different engineering fields can be discovered efficiently. This model can support further semantic integration and interoperability of the models, e.g., by using the Engineering Knowledge Base (EKB) approach [4, 12].

The remainder of this paper is structured as follows. Section 2 summarizes related work on signal change management, semantic integration and process modeling and analysis. Section 3 identifies the research issues. Section 4 develops the solution approach to discover model for signal change management in complex automation systems. Section 5 describes the evaluation based on signal change management processes. Section 6 discusses benefits and limitation of model discovery approach; and finally section 7 concludes the paper.

2. RELATED WORK

This section summarizes related work on signal change management, semantic integration technologies and process analysis approach as ways to build models for heterogeneous engineering areas.

2.1 Signal Change Management

According to the Meriam Webster dictionary, a signal can be defined as an object used to transmit or convey information. In this paper we define a signal as a common concept for linking information between disciplines. Thus, signals are not limited to electrical signal (wiring) in electrical engineering, but also include mechanical interfaces in mechanical engineering and software I/O variables in software engineering. In complex automation systems, we define relationships between different kinds of signals from different engineering fields and use them to collaborate and communicate.

Formerly, domain experts used manual change management approaches like in [1] to manage signal changes between different engineering fields. Manual changes use documents to manage changes between different engineering fields in the system. By using a primarily manual approach, the researchers collect the signal lists from each engineering field and then connect relationships between different engineering fields manually. If there is any signal change in one document, then the change has to be mapped to the relationship document and all relevant stakeholders have to find out which other signals in different engineering fields could be affected with this change. Manual change handling is costly and error prone. Thus, signal change handling automation is a promising research area to improve product and process quality.

Research on signal change management in product lifecycle management (PLM) context is done by e.g., Horvath and Rudas [11]. They propose a virtual intelligent space for engineering (VISE) to manage signal change and enhance decision making characteristics of PLM. VISE is a highly integrated application of recent CAD/CAM, human computer, collaborative, product data management, Internet portal, and intelligent information processing techniques in PLM system. The authors introduce the concept of change affect zones (CAZ). CAZ comprises a set of engineering objects on which a change may have any effect. Objects in an affect zone may be both inside and outside of a virtual space. So, the new changes/modifications or conflicts will be handled in CAZ before they are executed.

2.2 Process Modeling and Analysis

Process analysis approaches focus on analyzing (engineering) process data collected during the systems operation. Process analysis approaches have been applied to some types of complex systems, for example workflow management systems, Enterprise Resource Planning (ERP), and Customer Relationship Management (CRM) systems. Van der Aalst et al. [16] used workflow technologies to illustrate the structure of the operational processes of a system. Workflow technology provides event data that could be useful for process analysis in software engineering (SE) by enabling particular models that link basic tool events to process/workflow events [16].

Van der Aalst et al. [16] also used stored events, which refer to tasks and process cases originating from people/tools/systems, to monitor and analyze real workflows with respect to designed workflows. This approach is called process mining and can be used for process discovery, performance analysis, and conformance checking. The approach has been implemented in the open source tool ProM2 and can be used to discover the process model based on the available event log, analyze the performance of the processes, and suggest possible process improvement candidates.

Ferreira and Ferreira [8] proposed a reusable workflow engine based on Petri Net theory as a basis for workflow management. They introduced the workflow kernel, a prototype implementation of common workflow functionality which can be abstracted and reused in systems or embedded in applications intended to become workflow-enabled. The workflow kernel is based on common workflow functionality from several workflow engines, while the Petri net theory can be used as a process representation language for process analysis.

Sunindyo et al. [15] proposed an approach to monitor, analyze, and improve tool-based engineering processes. Main idea is to generate an interoperability model based on event-based process analysis activities to link heterogeneous software engineering tools.

2.3 Semantic Integration

Semantic integration is an approach to solve problems from an intention to share data across disparate and semantically heterogeneous data [9], which are including (a) the detection of duplicate entries, (b) the matching of ontologies or schemas, (c) the

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1 http://www.merriam-webster.com

2 http://www.processmining.org
modeling of complex relations in different data sources, and (d) the reconciliation of inconsistencies [13]. One of the most important and the most actively studied problems in semantic integration is how to establish semantic correspondences (mapping) between vocabularies of different data sources [6]. Hence, the application of ontologies as semantic web technologies to manage knowledge in specific domains is inevitable. There are five reasons to develop ontology, i.e., (a) to make domain assumptions more explicit, (b) to share common understanding of the structure of information among software agents or people, (c) to enable reuse of domain knowledge, (d) to analyze domain knowledge, and (e) to separate domain knowledge from the operational knowledge [14].

Moser et al. [12] introduced the Engineering Knowledge Base (EKB) framework as a semantic web technology approach to address challenges from data heterogeneity which is applied in the production automation domain [12]. Biffl et al. [4] also used the EKB framework for solving similar problem in the context of Open Source Software Projects. This EKB framework is applicable to solve semantic heterogeneity problems in other automation engineering systems.

3. RESEARCH ISSUES

Complex automation systems, like power plants, need to handle a high amount of data, e.g., up to 40,000 signals originating from different engineering fields. Stakeholders need to manage these signals to enable signal data consistency within the project. Thus, efficient and effective signal data management approaches are required to handle signal changes properly. In addition, individual engineers may not pay attention to signal data management but keep focused on their individual engineering work within their discipline, i.e., engineers from different fields don’t have to deal with the new tools and data formats that make their work even more difficult.

Other challenges in the signal change management include how to integrate the signal data originating from heterogeneous data models and tools. Figure 1 shows the requirements of mechanical engineers, electrical engineers and software engineers to share related signal data. The mechanical engineer uses different formats of data than the electrical engineer and the software engineer do. The challenge is how to integrate signals from heterogeneous data models/tools (1). By using a so-called “virtual common data model” [12], the different engineers can share their related data from electrical to mechanical signals and to the software variables. The “virtual common data model” becomes a foundation for mapping proprietary tool-specific engineering knowledge and more generic domain-specific engineering knowledge to support transformation between related engineering tools. It is “virtual” because actually there is no need to provide a separate repository to store the common data model. The management of the common data model with respect to different engineering fields is done via a specified mapping mechanism. The mechanism of the “virtual common data model” approach includes 5 steps: (a) Extraction of tool data from each engineering field; (b) Storage of extracted tool data into its own model; (c) Description of the tool knowledge for each engineering field’s tool; (d) Description of common domain knowledge; (e) Mapping of tool knowledge to the common domain knowledge. This work should be done carefully to obtain a complete list of signal mappings from the electrical to the mechanical and the software engineers. In real systems, stakeholders could also include people from other engineering fields.

This semantic integration challenge can be solved for example by applying semantic integration approaches like the Engineering Knowledge Base (EKB) framework [4, 12]. Other challenges are...
to manage version of signal changes across engineering disciplines and to manage common concepts based on the semantic integration (2). The research question is how to discover the process model from the actual data provided by heterogeneous engineering fields? Based on this research question, we can discover the structure across heterogeneous data models/tools and their interactions and we can identify the need for the semantic integration to link heterogeneous data models and tools.

Linking heterogeneous disciplines can enable a so-called end-to-end test (see Figure 2) to trace signals from hardware sensors to software variables across system borders. This approach supports defect detection during development and changes.

Figure 2. Interaction between different engineering fields.

Figure 2 shows the interaction between different engineering fields in managing the signal changes. Three different engineers, namely mechanical engineer, electrical engineer, and software engineer, typically share a lot of signals that are connected to each other. These relationships should be maintained in such an Engineering Knowledge Base, such that when some changes happen in one engineering field, they can be propagated to other engineering fields automatically or semi-automatically.

The evaluation is done by comparing the manual signal change management process and the automated/semi-automated signal change management process after applying the process model discovery approach to reveal semantic requirements in engineering processes across different engineering fields.

4. USE CASE

To show how to manage interoperability between engineering tools in the complex automation systems, we use a signal change management use case from mechanical to electrical and software engineer. Figure 3 illustrates how to merge different signals (and changes) and resolve conflicts between signals coming from different disciplines manually. The conceptual steps are as follows:

(1) The mechanical engineer executes changes in the mechanical plan that will also affect the tool data.

(2) The mechanical engineer manually makes a difference analysis for interaction with other engineering tools, to check whether there is any conflict with other engineering tools data.

(3) The mechanical engineer makes manual propagation to mechanical engineering tools and software engineering tools.

(4) The mechanical engineer and the software engineer execute changes in their mechanical plan and software development environment.

5. RESULTS

For discovering the interoperability model for signal change management processes in the design time and runtime of complex automation systems, we collect process event data from each engineering field, e.g., electrical, engineering, and software engineering. By using the ProM tool, we conduct an analysis to discover the underlying process model by applying the Alpha Algorithm [5] to the collected data. The work of Alpha Algorithm is based on discovering transitions which are causally related between different event traces. From collected event log data as an input, we can discover a set of related transitions from all event traces. For each tuple (A,B) in this set, each transition in set A causally relates to all transitions in set B, and no transitions within A (or B) follow each other in some firing sequence. We refine the set by taking only the largest elements with respect to set inclusion.

Figure 3. Manual Signal Change Management.

The output is a workflow net that connected each event trace to other related event traces via transitions [5].

Error! Reference source not found. shows the results of the model discovery analysis by using the Alpha Algorithm [5]. Here we have 4 different scenarios of the process model of the signal change management process.

(1) no conflict: the mechanical engineer executes changes and performs a manual difference analysis to other engineering fields via interaction between mechanical engineering plan, electrical plan, and software development environment. The mechanical engineer manually propagates changes to
The electrical engineer and software engineer execute changes in their environments.

(2) **normal conflict**: after manual difference analysis the mechanical engineer starts managing conflicts and resolves the conflicts, by modifying the old signal with the new signal. If the conflicts are resolved, the mechanical engineer transforms the change to other engineering fields.

(3) **critical conflict**: almost the same as the normal conflict. The difference is in the action after managing the conflict is over. The mechanical engineer has to remove the signal and send a notification to the electrical engineer and software engineer. The electrical engineer and software engineer will consider this as a critical conflict and decide whether to accept the signal removal or reject it.

(4) **looping condition**: if the electrical engineer and software engineer reject the signal removal, then there will be any option to argue on signal change on the electrical engineers side. Hence, the situation loops back to the condition before the change is transformed to other engineering fields.

From Figure 4, we can suggest for signal change management process improvement, by collecting and integrating the heterogeneous signal data models and tools from different engineering fields using automation service bus (ASB) [3] and EKB [4, 12]. ASB technically integrates heterogeneous tools while the EKB semantically integrates the heterogeneous data models of electrical engineers, mechanical engineers, and software engineers.

ASB is an approach similar to the “Enterprise Service Bus” in the business IT context [10] for complex automation systems engineering. The current “Enterprise Service Bus” approach is applied in the business IT context and the most of its implementations are making some design assumptions, e.g., service will always be online and resources (computing, network bandwidth, memory) are not the main issues of the design. These assumptions are not suitable with the requirements of the signal change management. Thus the ASB has to be designed more lightweight and be able to bridges technical gaps between engineering processes, models and tools for quality and process improvements [2]. Engineering components are connected to the ASB via connector components, which allows addressing all deployed components as services via the ASB. The ASB integrates components in both office-like design and onsite environments with a common integration architecture but different implementations [3]. In signal change management, the different tools to manage different signals from heterogeneous engineering fields are connected to the ASB via connector components. Each tool is treated as a component. The communication between components is also managed by the ASB, so when there is a signal changed in one tool it will be communicated via ASB and distributed to other tools automatically.

The EKB is a semantic-web-based framework, which supports the efficient integration of information originating from different expert domains without a complete common data schema [12]. The EKB framework stores the engineering knowledge in ontologies and provides semantic mapping services to access design-time and run-time concepts and data. The EKB framework aims at making tasks, which depend on linking information across expert domain boundaries, more efficient [12]. The EKB is connected to other tools via the ASB. In the signal change management, the EKB plays a role as semantic integration between different signal data from heterogeneous engineering fields. Each signal is stored in the ontology as a base of EKB together with its relationships to other signals. The changing of signal in the ontology means the modification of the signal entity in the ontology and its relationship.

The result of the signal change management improvement can be seen in Figure 5. It shows the usage of ASB and EKB to improve the signal change from mechanical engineer to electrical engineer and software engineer. (1) The mechanical engineer executes change in his mechanical plan. (2) The mechanical engineer checks in the change and makes difference analysis by using ASB and EKB. (3a & 3b) The electrical engineer and software engineer check out changes from ASB and EKB.
6. DISCUSSION
In this section, we discuss the benefits and limitations of the model discovery approach compared to the manual approach.

The benefits of the model discovery approach are as follows. (1) The model, which is obtained from the model discovery approach, is more precise and accurate because it is generated from actual event data from different engineering processes. (2) The model is easier to maintain and change. If some modifications of the system happen, we can collect the new event log data and run the process mining tool to get the latest model. (3) This model can be used to understand and learn the whole signal change management processes in the system. It also supports model-driven interoperability for other purposes, e.g., decision making and signal defect detection.

The limitations of this approach are as follows. (1) We should provide complete event log data from each engineering processes for model discovery. (2) The ProM tool has limitations in managing the inputs format, so we should transform the processes event log data to ProM format (Mining XML).

From this discussion, it is possible for other model driven interoperability systems to adapt the model discovery approach to get their process model immediately, rather than building from the scratch and improve later via several iterations.

The alternative of the process model discovery approach is making interview sessions for each engineer from different engineering fields to acquire the requirements to make a model. This model should be consulted between engineers to obtain an integrated view on the model from different engineering perspectives that support interoperability between different engineering fields.

7. CONCLUSION AND FURTHER WORK
Collaboration and interaction between different engineering fields are critical issues in heterogeneous engineering environments because individual disciplines apply different tools and data models. This heterogeneity hinders efficient collaboration and interaction between various stakeholders, e.g., mechanical, electrical, and software engineers. Semantic integration based on common concepts, e.g., signals, and increase collaboration efficiency and effectiveness. In addition, process observation based on event data is a promising approach for identifying the current (real) process workflow, measurement data, and the foundation for process analysis and improvement.

In this paper, we have explained the usage of a process model discovery approach to derive the model immediately from the actual engineering process data and identified improvement options for increasing process quality. We applied a signal change management process to illustrate the basic concepts, semantic integration approaches, and process improvement based on collected and analyzed event data.

We found that this approach is easier to be adapted in already-running systems which consist of different tools and data models for each engineering area. This approach can also be adapted and generalized to other model-driven interoperability systems.

Future works will include the application of the process model discovery approach to other problem domains and exploring the idea how to detect defects in signal change management and how to make decision on signal change management based on prior experience. We will develop a framework to prepare process model discovery for signal change management in different engineering fields, such that the process model discovery and other process analysis approach can be implemented more effective and more efficient.

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9. REFERENCES


