AutomationML in industry 4.0 environment: A systematic literature review

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Abstract. AutomationML is an open neutral XML based data exchange format used in automation systems. It has come into the public for more than 10 years and is being used in many different areas in all kinds of manufacturing applications, such as digital twin, reconfigurable manufacturing systems, heterogeneous data exchange, etc. However, no comprehensive literature review on the research and application progress of AutomationML has been found since the initiation of AutomationML. Based on the study and analysis of AutomationML related publications, this paper gives a detailed illustration on the state-of-the-art of AutomationML. Firstly, the background and terminologies related to AutomationML are introduced. Secondly, the paper applies a methodology to collect AutomationML related publications, on which an analysis based on a multidimensional literature classification is conducted. Thirdly, according to the analysis results, current research status and whether AutomationML can meet the requirements for industry 4.0 environment are discussed. Finally, conclusion and outlook are illustrated in the end.

Keywords: AutomationML, Digital twin, Reconfigurable manufacturing, Heterogeneous data exchange, Literature review.

1 Introduction

In an industry 4.0 production environment, multiple different engineering disciplines are involved throughout the product life cycle [1]. The tools used by these disciplines are quite different, which leads to a broad "heterogeneous tool landscape" [2]. To efficiently integrate this landscape, data exchange between these tools is an obvious bottleneck waiting to be resolved [3].

To solve this problem, Daimler AG initiated the foundation of a consortium together with leading vendors and users of automation technology in 2006 [4]. The aim of the foundation is to develop a neutral data exchange format usable within the engineering process of manufacturing systems to exchange data among multidisciplinary tools. The consortium named this neutral data exchange format 'AutomationML', short for Automation Markup Language. The first version of AutomationML was brought to the public at the Hannover fair in 2008 [3]. Its original application scenario is the description of the static structure of a plant's shop floor [5].

With the continuous development of industry 4.0 technology, manufacturing enterprises have to operate in a dynamic way to meet the diverse needs of customers [6]. This requires manufacturing systems to be flexible and reconfigurable enough to respond to orders from customers [7]. At present, the authors are trying to find a solution for a real-time reconfigurable digital twin system, in which the digital model can automatically change itself to reflect current situation of the production system according to the reconfiguration of the physical system. 'Digital twin' is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin [8]. This means that the digital model should always be consistent with the physical model. Due to the increasing flexibility of nowadays automation systems, having an up-to-date digital twin at all time is a great challenge. Therefore, an efficient way of bidirectional data exchange between the physical and its digital replica is indispensable. The authors believe that AutomationML could give an answer to this requirement.

This paper illustrates the state-of-the-art of AutomationML based on a systematic literature review. The question we are attempting to address is whether AutomationML can meet the requirements for industry 4.0 applications in general and for the generation of digital twins more specifically.

The remainder of the paper is structured as follows. In section 2, a general overview of AutomationML is presented based on an example. Both the content and the architecture of AutomationML are discussed. In section 3, a methodology which is utilized to collect AutomationML related publications is presented. An analysis method based on multidimensional literature classification is illustrated. Based on the analysis, the state-of-the-art of AutomationML is described and whether AutomationML can meet the requirements for making reconfigurable digital twin systems in industry 4.0 environment is discussed. In section 4, conclusion and outlook are made according to the illustration and discussion above.

2 AutomationML Overview

AutomationML is an XML based data format, which is open, neutral and free [4]. The top level core of AutomationML is CAEX, which is utilized to interconnect all kinds of data formats. As CAEX is object oriented, all kinds of engineering information can be stored in AutomationML objects. These objects are called internal elements in AutomationML hierarchy. Typical categories of the information stored in internal elements are plant topology information, geometry and kinematics information, logic information, reference and relation information, and other data formats [9]. An example of AutomationML can be found on the right side of Fig. 1. The represented hierarchy is the topology information of a robot cell. From the hierarchy it can be directly seen that: (1) The robot cell is composed of a robot station and a safety fence, (2) The robot station has a robot and a conveyer, (3) The robot includes a robot machine and a gripper. Besides the topology information, the node “GeometryInterfaceCollada” contains the geometry information of a robot cell component, which is referenced to an external geometry file in the format of Collada, while the node “LogicInterface-Gantt” contains the logic information of the robot cell, which is referenced to an external logic file programmed in Gantt chart.

As AutomationML contains all kinds of multidisciplinary interrelated information, it is important to ensure the modeling efficiency. Therefore, three class libraries are introduced: the role class library (RCL), the interface class library (ICL) and the system unit class library (SUCL) [9]. An RCL is a container of role classes (RC), which define the semantics of internal elements (IE), and each IE has to refer to an RC. Similarly, an ICL is a container of interface classes (IC), and an IC can be used to interconnect between 2 IEs, or to refer to an external file. SUCL is a library of system unit classes (SUC), and it can be used by easily dragging and dropping during the modeling of the instance hierarchy. By using these libraries, the modeling efficiency of AutomationML is greatly improved.

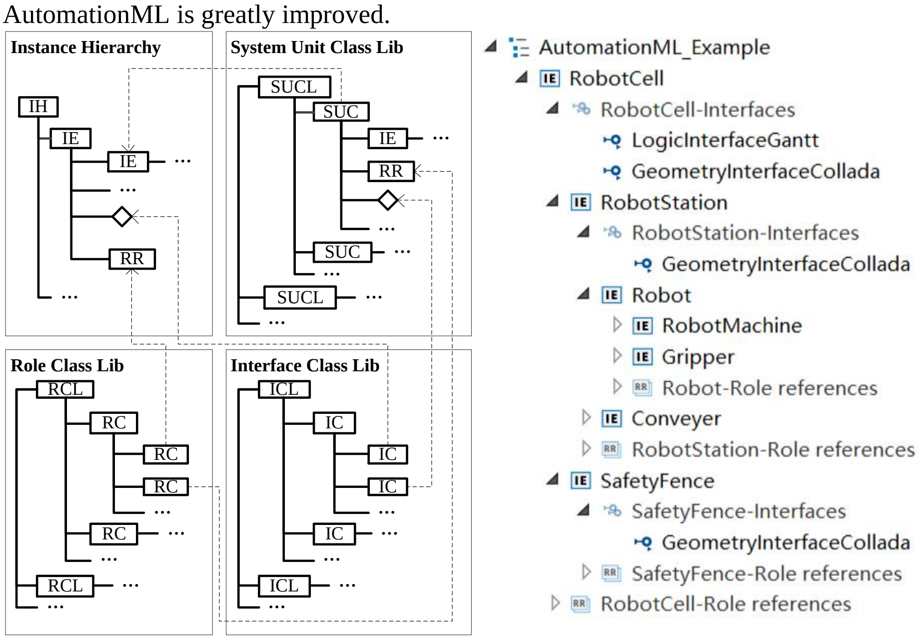

Fig. 1. AutomationML architecture and an AutomationML model example

3 Methodology and Discussion

This paper gives a systematic literature review on AutomationML. First, the authoritative website of AutomationML [4] is carefully checked. On this website, all AutomationML relevant research projects and technical documents are presented. Based on this, the authors have a clear understanding of AutomationML. Then, the authors use search engines Scopus, IEEE Xplore and Google Scholar to gather the publications containing the content of ‘AutomationML’. In this way, 195 AutomationML related publications have been found. Among the papers, the amount of conference papers is 174, while the amount of journal papers is 18. The rest of the publications are 2 technical reports and 1 doctor thesis.

The amount of AutomationML related publications by year is shown in Fig. 2. It shows that the publication amount trend is mainly ascending from 2008 to 2018. It means that AutomationML gains more and more interest of researchers. The authors believe the publication amount in 2019 will be more than the amount in 2018, as some publications in 2019 are still waiting to become publicly available. The publication count for 2020 is similarly affected.

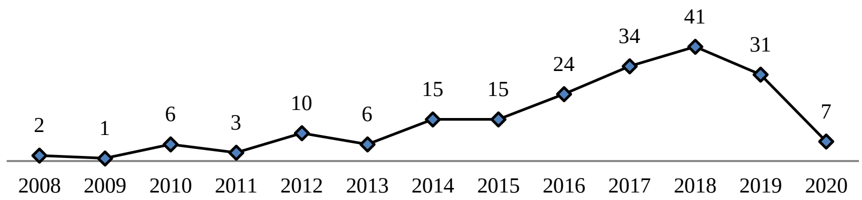

Fig. 2. The amount of AutomationML related publications by year until June 30, 2020

Fig. 3 shows the percentage allocation of the research fields related to AutomationML. According to the role of AutomationML, the research fields are divided into 6 categories, which are: modeling, data exchange, concept, maintenance, integration, and evaluation. Modeling (29%) and data exchange (27%) cover more than half of the publications, which verifies that AutomationML based automation system modeling and AutomationML based heterogeneous data exchange are research hotspots. Furthermore, concept, maintenance and integration related publications have a considerable share of overall publications, respectively 16%, 14% and 11%. Evaluation related research publications come in the last, which cover only 3%.

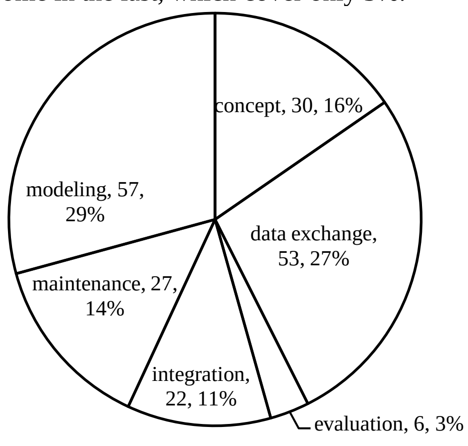

Fig. 3. AutomationML related research fields

- **Modeling:** The research field of modeling is using AutomationML based modeling method to express relevant information in AutomationML data format. The main question of this research field is what kind of modeling method should be used to describe the corresponding information. According to the publications, AutomationML based modeling methods are in many aspects, such as automation system modeling [10-11], communication system modeling [12-13], behavior modeling [14], process modeling [15], product-process-resource modeling [16], Asset Administration Shell (AAS) modeling [17], ISA-95 modeling [18], etc.

- **Data exchange:** This research field is focusing on doing data exchange based on AutomationML. This field is divided into two parts: (1) Data exchange between tools in the same field based on AutomationML, (2) Data exchange between AutomationML and other data formats. For (1), the data exchange paradigms include data exchange between 3D modeling software [19-20], between logical programming software [21-22], between simulation software [23-24], etc. For (2), there are methods for AutomationML to do data exchange with OPC UA [25], SysML [26], RDF [27], OWL [28], PMIF [29], etc.
- **Concept:** This field is about new conceptual methods on AutomationML related engineering. Breckle et al. [30] introduce an approach of an evolving digital factory containing and visualizing all generated information based on an AutomationML metamodel. Kiesel et al. [31] present an approach of an AutomationML-based AAS, which is able to handle heterogeneous data. Wally et al. [32] use the information stored in a separate B2MML document to define an alignment of two industrial standards, ISA-95 and AutomationML.
- **Maintenance:** This research field focusses on the development of new approaches for working with AutomationML. Winkler et al. [33] present an AML-Review process approach towards reviewing AutomationML model elements with tool support. Wimmer et al. [34] propose a dedicated query language for AutomationML. Hua et al. [35] present a concept learning approach in AutomationML using the DL-Learner framework. Ananieva et al. [36] develop an approach to detect and repair inconsistencies in systems modeled with AutomationML.
- **Integration:** In this field, AutomationML is a component which is integrated in all kinds of digital automation systems. Panda et al. [37] develop a Plug & Play retrofitting platform based on AutomationML and OPC UA, where Industry 4.0 compliant sensor systems can be attached, detected, and configured automatically to the existing production environment.
- **Evaluation:** This field is about the evaluation of AutomationML related aspects. Meixner et al. [38] draft a novel, flexible evaluation framework in the context of AML model storage, modification, and retrieval and to evaluate two particular data storage paradigms.

From the classification of AutomationML related publications, we can conclude in several aspects. AutomationML, a data format which came to public just more than 10 years ago, is gaining more and more attentions from researchers. It is possible to model all kinds of manufacturing system information in AutomationML and to do data exchange based on the combinations of AutomationML, OPC UA, AAS, ISA-95, etc. We can say AutomationML is a promising data format which shows great potential for modeling rapidly changing automation systems in order to efficiently obtain and maintain an up-to-date digital twin.

However, the publications on AutomationML based reconfigurable digital twin systems are very limited. Only 6 papers describe the relevance of AutomationML in combination with digital twins. 3 of them are in the research field of modeling [39-41], 2 of them only describe a conceptual design [42-43], and 1 paper illustrates a method of automatically generating the digital model based on AutomationML [44]. No reconfigurable digital twin system is indicated in literature.

The raising interest in digital twins and their applications in combination with the rise of mass customization, amplifies the need for a reconfigurable digital twin [45]. This may save a lot of effort for manufacturing enterprises, since the generation and maintenance of a digital twin is very time consuming. Therefore, the authors plan to make such a reconfigurable digital twin system. AutomationML will be used not only for digitally modeling the geometry and kinematic information, behavior and logical information, process information, etc. of the whole physical system, but also as a data exchange bridge between the digital model and the physical system. Plug-ins will be developed in both sides to ensure AutomationML based data transmission. AutomationML based real-time communication is also to be achieved.

4 Conclusion and Outlook

This paper gives a systematic literature review on the state-of-the-art of AutomationML. The authors classify AutomationML related publications into 6 categories according to the role of AutomationML. The majority of the publications is about what modeling method could be used for AutomationML (29%) and how to do data exchange based on AutomationML (27%). Furthermore, there are some publications that focus on conceptual descriptions (16%), maintenance of AutomationML files (14%) and the integration of AutomationML in real applications (11%). Only 3% of publications discuss the evaluation of AutomationML related aspects. According to a multidimensional literature classification, it can be stated that AutomationML is a promising data format to be used in an industry 4.0 environment. Continuously improvements due to current research will probably lift its potential even higher.

In the future, the authors are planning to develop an AutomationML based methodology to make a real-time reconfigurable digital twin system, in which the digital model can change synchronously along with reconfiguration of the physical model. Real time data exchange technology based on AutomationML will be used to ensure the equality between the physical system and its virtual replica.

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