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A Virtual Environment for the Management and Development of Cyber-Physical Manufacturing Systems ⋆

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Abstract:
Modern machineries are often cyber-physical system-of-systems controlled by intelligent controllers for collaborative operations on the productions of complex products. To assure the efficiency and effectiveness, a consolidation of concerns across managerial levels, product lifecycle stages, and product lines or families becomes necessary. This calls for a common information infrastructure in terms of ontology, models, methods and tools. For industrial manufacturers subjected to increased cost pressure and market volatility, the availability of such an information infrastructure would promote their abilities of making optimized and proactive decisions and thereby their competitiveness and survivability. This paper presents a virtual environment that constitutes an information infrastructure for the management and development of evolvable production systems (EPS) in manufacturing. It adopts mature modeling frameworks through EAST-ADL for an effective model-based approach. The contribution is centered on a meta-model that offers a common data specification and semantic basis for information management across product lifecycle, models and tools, both for resource planning and for anomaly treatment. A prototype tool implementation of this virtual environment for validation is also presented.

Keywords: Evolvable Production Systems (EPS), Cyber-Physical Systems (CPS), Model-Based Development (MBD), Domain-Specific Modeling (DSM)

1. INTRODUCTION

Due to the increased cost pressure and market volatility, the ability of industrial manufacturers to support efficient, agile and robust processes is of vital importance for their competitiveness and survivability. As a consequence, the manufactures have to pay increasingly more attention to production planning, resource deployment, and operation control. Meanwhile, the integration of state-of-the-art information and communication technology, computer software and hardware into modern machineries are fostering many new opportunities in the areas of autonomy, robustness control, and situation-aware adaptations. For example, one scenario could be that a set of machines perceive and communicate their respective operational situations and thereby automatically plan and synchronize their actions taking into account the overall production goals and risks. As a consequence of such integration, modern machineries are evolving from being physical to being cyber-physical (Rajkumar et al. (2010), Wolf (2009)).

Form an engineering perspective, the success depends on the availability of appropriate methods and tools both for effective controller development and for process management. In particular, for advanced decision making, novel methods and tools are necessary to capture the following concerns: 1. the operational constraints in temporal and spatial domains, 2. Knowledge about the preferred optimizations of machine resources under different circumstances, and 3. the interdependencies of operational decisions with various business constraints such as production costs and time. Moreover, a systematic treatment of uncertainties of observed and planned behaviors, as well as various failure modes of the machines, is necessary for advanced proactive decisions, and robustness guarantee, error handling and fault treatment.

This paper presents a study on the development of a virtual environment that adopts well-known system description frameworks for an effective model-based approach to the management and development of manufacturing systems with advanced cyber-physical features. See Fig. 1 below. This model-based approach advocates the use of models, conforming to a common semantic meta-model, not only for system development, but also as a basis for the embedded knowledge inference as well as the higher level process management decisions. This allows effective communications and decisions across product lifecycles, models and tools.

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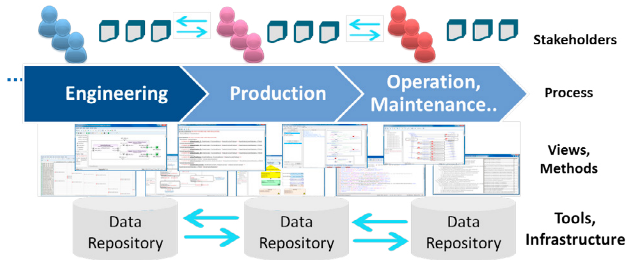

Fig. 1. Information exchange through social and technical means across the lifecycle stages of a system.

The content of this paper is organized into the following main sections:

- Section 2 introduces the key concepts of production systems being formalized as well as the EAST-ADL language being adopted as a fundamental framework for system modeling, information management, analysis and synthesis.
- Section 3 presents the meta-model underlying the design of a common modelling language for system description and information consolidation. By extending the EAST-ADL modeling framework, the approach exploits the support of several existing system description frameworks for the realization of an ontology for evolvable production systems (EPS).
- Section 4 presents a software tool implementation of the virtual environment, based on the DSM workbench MetaEdit+. Based on the meta-model, this tool provides the user-level support for an integrated specification of product&production features, abstract process, as well as the machine resources in terms of functional agents and physical equipments. We also introduce the related modeling support for requirements engineering, annotations of timing constraints, plausible errors/anomalies, as well as the approaches to analysis, design space exploration and optimization. This tool constitutes a prototype and a solid basis for further industrial validation.

2. SYSTEM CONCEPTS AND TECHNOLOGICAL PREDERENCES

2.1 System Concepts

An evolvable production systems (EPS) for product assembly consists of the following key aspects (See also Fig. 2)

- *Assembly Features* – relating to the parts of products to be assembled. For a product, the specification normally describes the number of parts and their corresponding geometrical and material characteristics as well as the preferred assembly methods. From a production point of view, each part together with its geometrical and material characteristics constitutes a *production feature* that can be of concern for the product composition.
- *Assembly Process* – relating to the plans of work *tasks* to be executed by the machine resources for the assembly of products. Each work task defines for one or multiple parts the required assembly operations or functions, such as moving and joining. In a process, the work task is also associated with constraints in regard to timing and synchronization, reliability and safety.
- *Assembly Equipment* – relating to the *machine resources* for the production. Normally, each machine resources offer some basic production skills, such as gripping and moving parts, or conducting negotiation with different machines for behavior coordination. Each resource has performance characteristics in regard to throughput and robustness.

A modern assembly line system is often implemented as a multi-agent system where a variety of interacting functional units, referred to as *agents*, collaborate dynamically to satisfy both local and global objectives (Maturana&Norrie (1996)). In order to achieve fully adaptability at the shop floor level, a novel design paradigm, referred to as *Evolvable Production Systems* (EPS) is first introduced in Onori (2002). One key notion is *mechatronic agent*, referring to a production unit (gripper, robot, etc.) that embeds a computer board on which agents are running to provide some production services in terms of skills (Onori et al. (2012)). The design depends the related process requirements (Onori&Barata (2009)). There are two types of skills; (1) Simple Skills; atomic services provided by the module which may or may not directly match a process, (2) Complex Skills; on the other hand abstracts and manages a composition of simple skills, necessary to the execution of higher level processes.

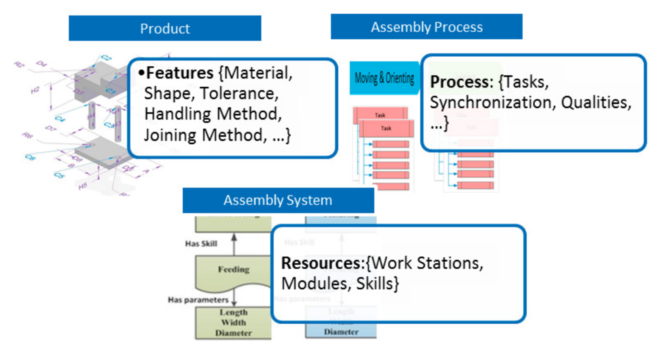

Fig. 2. Key aspects of an assembly system..

2.2 EAST-ADL as Base Technology to System Ontology

The EAST-ADL modeling framework (Electronics Architecture and Software Technology - Architecture Description Language), including a methodology and a modeling language, represents a key European initiative towards a standardized multi-viewed description of automotive electrical and electronics systems (EAST-ADL (2014)). It is a result of a series of consecutive projects: ITEA EAST-EEA, EU FP6 ATESST I and EU FP7 ATESST II, and EU FP7 MAENAD. We believe that EAST-ADL, by integrating many generic system description frameworks (e.g. SysML) and automotive specific methodological and technological considerations (e.g. RIF/ReqIF, ISO26262), provides a solid basis for enabling a model-based planning and management of vehicular assembly line systems. On the basis of EAST-ADL, language extensions and specializations will be developed to promote separation-of-concerns and thereby effective quality management of manufacturing systems.