GENERIC REFERENCE ARCHITECTURE FOR DIGITAL, VIRTUAL, AND REAL REPRESENTATIONS OF MANUFACTURING SYSTEMS

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Abstract*: Manufacturing companies are facing the challenging dilemma on how to achieve better quality products while reducing manufacturing costs and define the processes as environmentally benign. This is a challenge at the time when consumers are not willing to pay more. One of the ways this challenge can be met is to build better information structure and knowledge base that will support product development environment catering to multiple stakeholders with conflicting set of goals. This paper aims to outline a need for a common information architecture for saving and utilizing more realistic manufacturing parameters as a basis for improved product design and enhanced, cost efficient and sustainable manufacturing. It concentrates on the knowledge representation for combining product, process, and system knowledge into structural shareable reference architecture. The knowledge model's feasibility is tested in a holonic manufacturing environment.*

Keywords: reference architecture, knowledge model, sustainable manufacturing, holonic manufacturing

Introduction

Global economy has made design and manufacturing processes to become more and more distributed around the globe. Design teams are located possibly in every continent. In such a geographically and temporally divided environment, effective and proficient collaboration between design teams is crucial to maintain product quality, production efficiency, organizational competency and focus on sustainable products and processes.

Companies are interested on eco-friendly production if there are clear cost saving opportunities available, it affects positively on the brand, or it is required by the regulatory authorities. However, due to the lack of measures for evaluating the sustainability, lack of computational models of complex systems, lack of implementable trade-off analysis and structural knowledge models the realization of the sustainable processes cannot be done or verified inside the companies.

Harms et al. summarized that there are no real tangible benefits of the development of sustainable processes if the current production parameters, system utilization and equipment's use history is not also known (Harms et al. 2008). The survey conducted during the 6th Framework Programme Integrated Project, PISA-Flexible Assembly Systems through Workplace-sharing and Time-sharing Human-Machine Cooperation, has highlighted the challenges the companies are facing with in the successful re-use planning of the existing assembly systems. The survey revealed that there is a lack of experiences with the reuse of the process, insufficiently designed and prepared equipment, partially missing or incomplete life-cycle information and lack of holistic concepts for the reuse of the equipment (Fleshutz et al. 2008, Harms et al. 2008).

There is a need for open machine interpretable models and reasoning procedures, which are based on the parameters collected and filtered from the real processes for the holistic production management. Without the formal representation of the product, process and used manufacturing system the operational parameters and sustainability factors cannot be feasibly added into the evaluation of new generation products and manufacturing systems. Lack of information models also leads to the situation in which innovative design for sustainability cannot be fully realized.

The following chapters explains the possibilities for achieving better sustainability in the factory floor by outlining some of the measures needed to capture in to the knowledge model. The proposed reference architecture and the knowledge model are tested with a holonic manufacturing system.

Background

Sustainability in the Manufacturing

The multi-criteria for more efficient and sustainable production planning have several local optimization goals that are in trade-off between each other. The sustainability related factors which could be included into the trade-off analysis are maximum reuse of the assembly and manufacturing systems, minimal costs, minimal risk and/or maximal reliability (Harms et al. 2008), minimal energy, minimal CO_2 consumption (Heilala et al. 2008) and minimal material usage, minimal production time and efficient use of resources (Salminen et al. 2008). Depending on the need for change or improvement of manufacturing processes, there are different factors that are affecting the plan for sustainable manufacturing.

- New production facility/processes with new resources: investments for newer energy efficient equipment and freedom towards facility planning with extensive simulation models.
- New production facility/processes with existing resources: fewer investments for new machinery. The optimization lies on the re-usability of the machinery and on improving the production efficiency by redesigning the processes based on the measured values of performance such as busy-idle times, energy consumption during the production and better utilization of materials.
- Old production facility/processes with existing resources: minimal amount of investments for new machinery. Improving the sustainability of this scenario lies in the fine-tuning or redesign of the processes based on the measured values of performance such as mean time between failures, repair times, busy-idle times, and energy consumption during the production and better utilization of materials.

Currently the sustainability factors, which can be feasibly taken into account in design and simulation of manufacturing systems, are CO_2, NOX, SO_2 emissions and energy consumption of machines as Heilala et al. (2008) showed. However, energy consumption along the emissions could be traced into the manufacturing feature-level as well as to the system's life-cycle level for detailed simulation of different scenarios. This would require more detailed level description of products, processes, and resources complemented with real manufacturing parameters of the life-cycle states of each machine.

In order to reach sustainability in the factory floor, the production plan, utilization of resources and routing of material, parts, and products need to be considered as well. The machines in a factory floor are busy, blocked or idle state, however they are constantly online and continuously using energy even though there are no processes in the queue. There are ways to improve the efficiency of the overall utilization of resources by carefully selecting which machine would be best in given trade-off scenario. One of those is production planning and execution based on holonic manufacturing architecture, where the autonomous and cooperating holonic entities are self-configuring based on the production goal, which can be a trade-off based on the energy consumption, maximal amount of products, and used time.

Holonic Manufacturing Paradigm and DiMS

A holonic manufacturing system (HMS) is a way of organizing a manufacturing system to meet the challenges of fast changing production requirement. In an HMS, resource entities such as machines, tools, parts, products and operators have autonomous and cooperative properties and defined communication interfaces. These entities are called "holons," a word coined by combining "holos" (the whole) and "on" (a particle) following Koestler (1968). In an HMS, holons' activities are determined through the cooperation with other holons and the available context information, as opposed to being determined by a centralized mechanism (Guo 1994, Salminen 2008).

One of the holonic manufacturing paradigms is the Digital Manufacturing System (DiMS) concept, developed in Tampere University of Technology. The holonic entities – products, resources, and orders – are following the Product-Resource-Order-Staff architecture (PROSA). PROSA outlines the structure for basic holons: product holons, resource holons and order holons, which are connected with the process domain, production domain, and business domain (Salminen 2008).

In the DiMS framework, the knowledge is observed from three different viewpoints: digital entity, virtual entity, and real entity. Figure 1 illustrates the different domains used to describe the contents and the context of a holonic entity. The digital entity is the representation of the digital information, such as knowledge model, of the entity. The virtual representation of an entity is a domain for validation of the digital knowledge by different levels of simulations. The simulation can be used for example to analyze possible manufacturing scenarios, validation of planned processing times, and reachability of used robots and devices. The simulation model is connected to the digital entity via reference architecture. The real model is the actual test scenario where the operational parameters are collected and saved into the digital model (Salminen et al. 2008, Nylund et al. 2008),

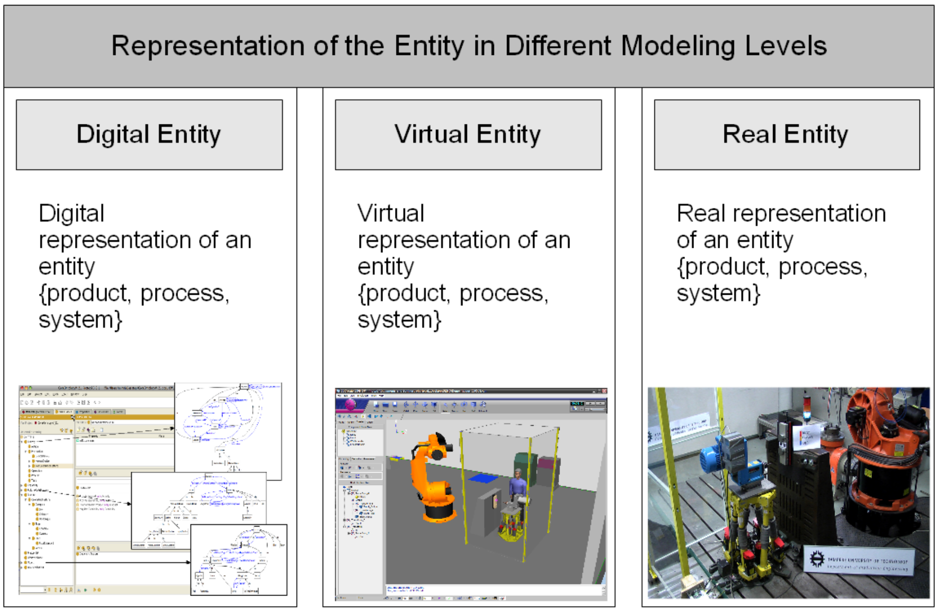

Figure 1. Knowledge representation in the DiMS framework

The DiMS concept aims for eliminating the waste - time, material or resources – by validating the digital model in the simulation environment and treating it as a hypothesis which will be proven for true or false in the real test manufacturing environment. The manufacturing plan is considered to be in the state of hypothesis when manufacturing context is changed. The hypothesis approach forces the manufacturing system to re-evaluate its performance and focus on continuous improvement, since the context is considered to be dynamic.

The DiMS does not describe the inner structure of a holon, its capabilities, or the detailed communication architecture. For representing the knowledge of each holonic entity and the context where the holons act, a structural knowledge model needs be defined.

Combining the Product Related Feature Information to the Process and System Description

The literature offers much unstructured information concerning the separate manufacturing entities or variables, referred as design domains later on the text, but detailed connection between these domains is hardly discussed. Rampersad (1994) in his research divided the overall assembly system requirements into three categories: product, assembly process and assembly system; he also developed the Integrated Assembly Model. Each of these variables consists of three elements, which have been set into three levels of abstraction (i.e. levels of complexity). Rampersad (1994) concentrated on the theoretical model of how the connectivity and constraints were shown in between of these three domains. Lohse (2006) continued developing the integrated assembly model by concentrating on the connectivity between assembly processes and available assembly systems. However, the connection between products and processes was in theoretical level and product knowledge was not used as a basis for reasoning on possible assembly process or systems.

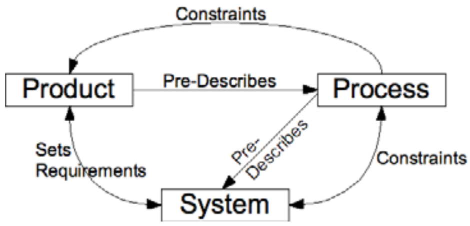

Figure 2. Product, Process and System Connectivity Graph

Figure 2 shows a model that describes the connectivity between products, process and system domains (Lanz et al. 2005). The characteristics of the product are pre-describing the set of the processes needed to manufacture and/or assemble the product. The description of the product defines constraints for the suitable processes. The processes are pre-defining the system requirements and constraining the set of systems. The system domain includes the defined resources and functions related to specific resource types. The products and systems are defined via geometrical and non-geometrical features, which are described through a generic Product-Process-System model (Lanz et al. 2008a).

Implementation

In order to support the integrated information architecture that represents realistic behavior of products, processes, and systems, a generic domain ontology was created. The ontological modeling provides simplification and categorizing of the knowledge into typified but still flexible form.

The domain ontology, Core Ontology, illustrated in Figure 3, was created with Protégé 3.3.1 Owl editor and visualized with GraphViz. The Core Ontology consists of three domains for describing a content and context of a model. The product section of the ontology has four main levels *product, sub-assembly, part,* and *feature*. The process ontology defines the activities required by the product via actors from the system ontology. The activity class is the root class in this domain.

Processes are defined, for instance, as *Part Manufacturing, Assembly, Testing* and *Packaging*. In the case of the assembly process, the tasks are such as move, retrieve, release, and join. If the assembly task belongs to the joining class then the operations can be, for example, screwing, gluing, insert, and press-fit. The actions are the most basic functions or tool paths relating to the features. The connection between products and processes is done in such way that the *Processes* are connected to the *Product* level, *Task* to *Sub-Assembly*, *Operations* to *Part,* and *Actions* to *Geometric Feature* level. This connectivity allows organizing a generic process model in different levels of abstraction depending on whether the detailed product information is available (Lanz et al. 2008b).

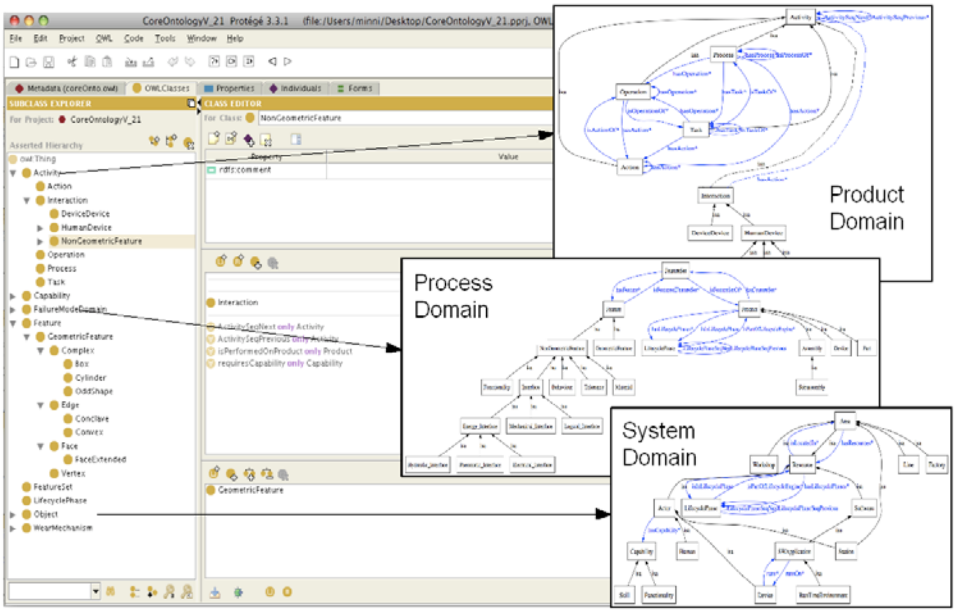

Figure 3. Core Ontology

The resource model consists of classes for *devices*, *actors*, *tools*, and *area* (having subclasses for *factory*, *line* and *station*) for describing the context of the manufacturing environment. The model allows the occurrence of multiple devices such as robot and drill combinations. Software blocks are also considered as resource models, which can be connected to the corresponding device model. Each of the resources has classification for *capabilities* for describing what the resource can do.

The technical implementation, the Knowledge Base (KB), was built to be a system where the knowledge could be stored and retrieved for and by different applications varying from the product and process design to simulation and manufacturing. Figure 4 shows the implemented architecture for the knowledge base. To achieve this design the following tools were used to facilitate the approach: Apache Tomcat web server, Apache 2 web service engine, Jena semantic web framework, Pellet Owl reasoner, and Postgre database.

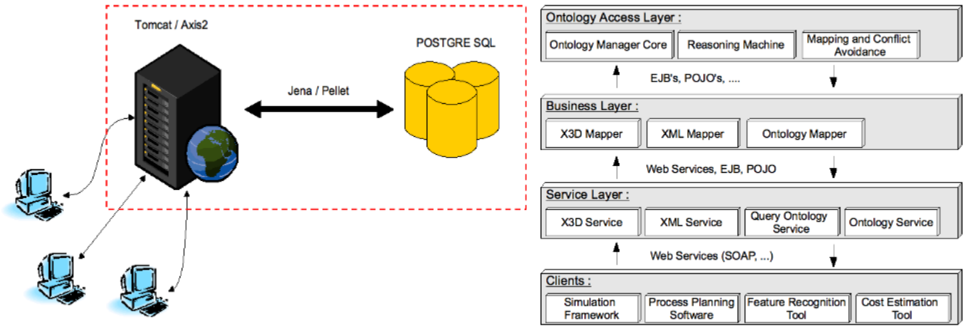

Figure 4. Implementation of the KB

Service Oriented Architecture (SOA) was chosen for this implementation. SOA is a standardized architecture that can be implemented by using a set of Web Services, which are software systems designed to support interoperable machine-to-machine interaction over a network and an interface described in a machine-processable format e.g. WSDL (Web Service Description Language). Other systems interact with the Web Services in a manner prescribed by its description using SOAP-messages (Simple Object Access Protocol) conveyed using HTTP (Hypertext Transfer Protocol) with an XML (eXtensive Mark-up Language) serialization in conjunction with other Web-related standards. With the use of Web Services client applications can interact by sending or retrieving knowledge from the KB (Lanz et al. 2008a, 2008b).

Case – Connection of Digital, Virtual and Real Entities

By utilizing the DiMS concept combined to the information architecture a laboratory demonstration was conducted. The aims for the knowledge model point of view are 1) the feasibility of connecting different actors under the same reference architecture and 2) update of the model with simulation data and real manufacturing values. The production paradigm followed the principles of DiMS concept treating the robot unit (a drill attached to Fanuc 200iB parallel kinematics robot and Safety Eye System from Pilz), fixture unit (fixture and camera), operator, and order software as holonic entities while the technical solution utilized various design and analysis tools interconnected through KB illustrated in Figure 5.

The product knowledge of the test part A (a cylindrical object with two holes) and the part B (a similar cylindrical object with four holes) were analyzed with a feature recognition tool Pro-FMA. The found features were categorized, located, and connected to the process sequences. The knowledge of the part was first sent to the simulation environment, Visual component's 3DCreate, where the virtual manufacturing was conducted based on the known resources.

The service request as a work order was generated by the operator and published via Web Services. The selected part's information was retrieved from the KB. If the processes for each feature were defined properly and the real drilling sequence attached to the product model, the information was sent to the robot unit's work queue. The robot unit was by default in idle state. For being able to start the work cycle, the robot unit needed the process approval verification (the part is fixed and in right place) from the fixture unit before starting the work cycle.

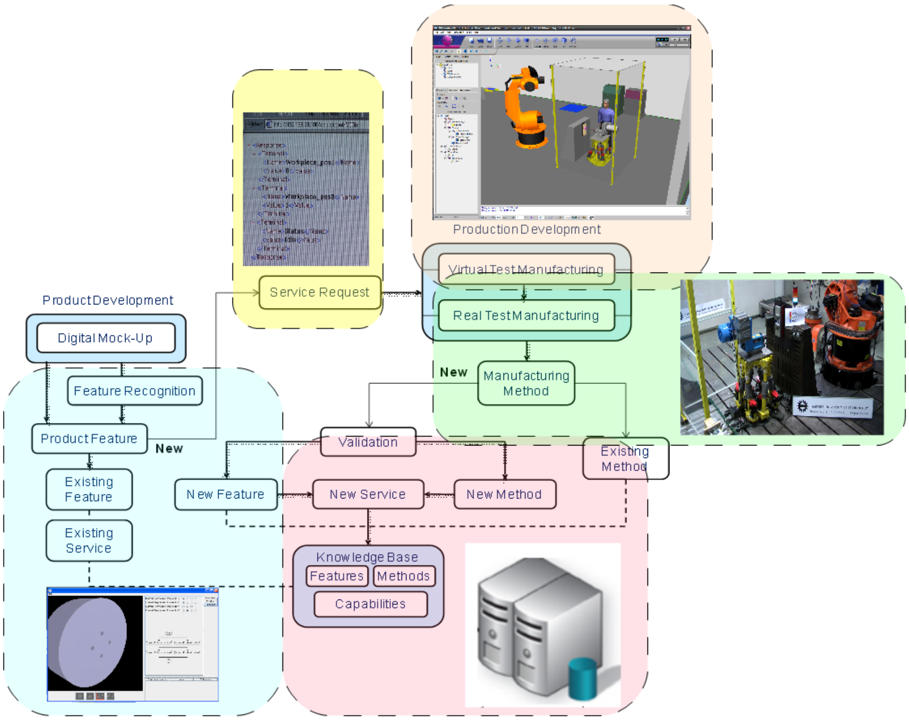

Figure 5. Laboratory demonstration set-up

The robot unit carried out the drilling procedure and the sensors attached to the drill collected and sent the machining values (such as *id*, *F mean*, *F max*, *AE mean*, *AE max*, *g max*, and *g sdev*) dedicated to each feature and the corresponding process sequence back to the controlling interface. The controlling interface returned the operational values back to the KB. The product model was updated with real values and the simulation times for features were validated.

Conclusions

The approach introduced here aims to explore the possibilities of utilizing the product-process-system related information in an environment where different design and execution systems are contributing and retrieving information in different levels of abstraction. The aim was to utilize the knowledge created in a heterogeneous environment and contributed into a reference architecture maintained by the KB as a basis for automatic process generation and simulation of assembly systems in different levels of abstraction. The current status allows the meaning of the content to be combined with proprietary/closed formats by offering references and content description for the models and allows this architecture to be used in the holon based manufacturing environment. The model itself can capture the information of the context during the time of operation.

Future Work

In future more of the real working conditions will be saved to the part's production history as well as single resource's operational history. By saving this information, the back tracking of the systems' conditions, energy consumptions or parts' design features becomes feasible. In addition, the tool's current use state and other machinery's characteristics can be saved and used for improving the process efficiency, pinpointing the possible quality problems related to the part's features or single machines and overall improvement of various processes. The CoreOntology used here is very generic by nature and the future work consists among others, of developing more detailed resource models to capture capabilities, geometric properties and other metadata relevant to that particular resource. The models need to be improved in such manner that they can capture and convey the operational parameters of each resource into the simulation environment where the different production scenarios can be tested before applying into the factory floor. There exist possible models, such as Core Manufacturing Simulation Data (CMSD) from Riddick & Lee (2008), for representing the basic process and resource information, but in order to fulfill the requirements from the DiMS framework there is a need for development of new models or extensions for the existing ones.

In order to enhance the processes inside the virtual factory or real factory the fastest, cheapest and most energy efficient production method needs to be calculated based on the real production parameters. The multi-criteria needs to include the aspects of resource utilization levels, device reliabilities, energy consumption and other sustainability related factors which adjustment relates to the costs of the operations.

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