A Model-based Approach to Control, Reconfigure, and Optimize Flexible Production Lines

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***Abstract*—The fourth industrial revolution (Industry 4.0) has modified the modern manufacturing structure, leading to the introduction of new technologies (*i.e.*, smart sensors, collaborative robots, predictive maintenance, etc.) and new paradigms such as Service Oriented Manufacturing (SOM). On the other hand, classical monolithic information systems are still based on old concepts of manufacturing. Therefore, they are not able to exploit the maximum capabilities of these new technologies. This is especially true for small and medium enterprises which cannot afford to replace all their information systems. In addition, due to the variability of production processes, each manufacturing is completely different from the others, creating a more complex environment. In such a context, a promising direction is to model the functionalities and requirements of production plant through models, and then exploit the knowledge represented within such models to adapt the developed approaches. This thesis proposes a model-based software architecture, that allows controlling, reconfiguring, and optimizing service-oriented manufacturing systems, by exploiting the knowledge represented within models. Thus, it extends and automated the Supervisory level of the classical automation pyramid by interacting with both the Manufacturing Execution System (MES) (planning level) and with the production line.**

***Index Terms*—Process modeling, Software architecture, scheduling**

I. Introduction

In the past years market requirements have changed, moving towards more customized products. Therefore, to keep up with these new requests manufacturing technologies must evolve to cope with the increasing unpredictability of modern society conditions. "Industry 4.0" [1] is meant to assist this transformation, proposing a set of *production systems development guidelines* to a wide range of engineering disciplines. Among the promises of the Industry 4.0 trend, the concept of *reconfigurability* stands out as a key factor to quickly adapt the production to sudden market changes [2]. The reconfiguration of a production line is a multi-layered problem, bridging business aspects to automation control. In this context, one of the emerging approaches in industrial automation is SOM, where functionalities of machines and software components are exposed as services across the manufacturing. At the same time, the adoption of SOM-based approaches technologies in a production environment is far from being an easy task, since it raises the complexity of the software infrastructure.

Model-based knowledge representation is the key that allows to properly manage such complexity. It consists of modeling knowledge through modeling languages within models. In

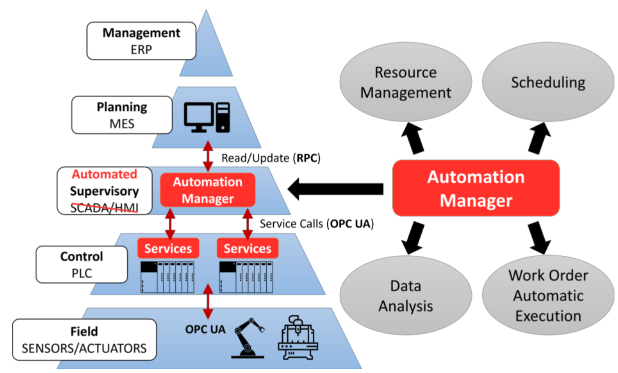

Fig. 1. The classic *Automation Pyramid* (on the left, in blue), and the localization of the *Automation Manager* (in red) proposed in this thesis, and modifying the software architecture.

the past years, many different languages have been proposed to model different parts of manufacturing. For example, Business To Manufacturing Markup Language (B2MML), which is focused on modeling business processes, and Automation Markup Language (AutomationML) which allows to model the topology, kinematics, and interaction with machines. Recent works [3], proposed System Modeling Language (SysML), as unified language to model manufacturing knowledge and also enabling models reuse. SysML provides an intuitive graphical language, explicitly tailored to express the structure and behavior of complex systems such as Cyber-Physical Production System (CPPS). Thus SysML aims at easing the specification and modeling phase for all the three levels of the production model. Furthermore, SysML supports the XML Metadata Interchange (XMI): an XML-based format easing data exchange, manipulation, and analysis. Thus, allowing to easily implement procedures able to analyze and manipulate the data carried by models.

This thesis aims to fill the current gaps in the transition toward Industry 4.0, by proposing a SOM software architecture that eases the integration of new technologies and methodologies within manufacturing, such as dynamic reconfiguration, predictive maintenance, reactive scheduling, etc. Another key point of this work, no less important is the formalization of the manufacturing knowledge represented within models spacing from the information systems to the machines. This will allow exploiting the knowledge expressed in such models to develop new model-based methodologies and technologies on top of the proposed software architecture.

II. Achieved Results

To integrate new technologies and methodologies within manufacturing it is necessary to interact with also all the information systems that are already present. Therefore, to ease the integration and the development of these new technologies in [4] we proposed a software framework called *Automation Manager*, which acts as a middleware between the production line and the MES, as depicted in Figure 1. Furthermore, it automated the third level of the automation pyramid by implementing a dynamic scheduler, advanced data analysis, resource management, autonomous work order execution, and a module that enable communication with other custom components. It consists of three different layers and many sub-components; the first layer contains the *Driver* that manages the communication between machines and theMES; the second layer contains the *Core*, which implement all the functionalities necessary to develop new applications; the third layer contains the *Applications* which implements custom functionalities.

Then, in [5] we proposed an extension of the classical representation of production processes represented through SysML. Rather than using standard representations such as Resource Task Networks (RTNs) and State Task Networks (STNs), that formalize production recipes as a directed graph (top part of Figure 2), a multi-level, hierarchical model for production processes. The model consists in three levels as depicted in Figure 2, each of them modeling a different abstraction of the production process.

- the *task level* consists of a task-resources graph. It allows describing the bones of the production process, which are the tasks, their dependencies and the machines on which such tasks can be allocated.
- The *service level* refines the concept of "task", describing the sequence of steps required to be carried out to complete the task.
- The *machine function level* describes the interactions that need to take place between the control software and the machine implementing a service as a directed graph.

In addition in [5], we also proposed a reactive scheduling algorithm that exploits the knowledge represented within the three different abstraction levels of the proposed model. The algorithm takes advantage of the additional information to make a more precise decision on whether a process can be interrupted, interleaved, and preempted, thus improving the performance of the production systems.

Then, in [6] we demonstrate the impact of correct estimation of tasks transport time in scheduling. We also proposed a heuristic based on randomization, which is able to find near optimal schedule for task processing and transfer time between equipment in few seconds.

III. Thesis Completion

In the near future, I plan to improve and extend the proposed methodology by first integrating state-of-the-art techniques

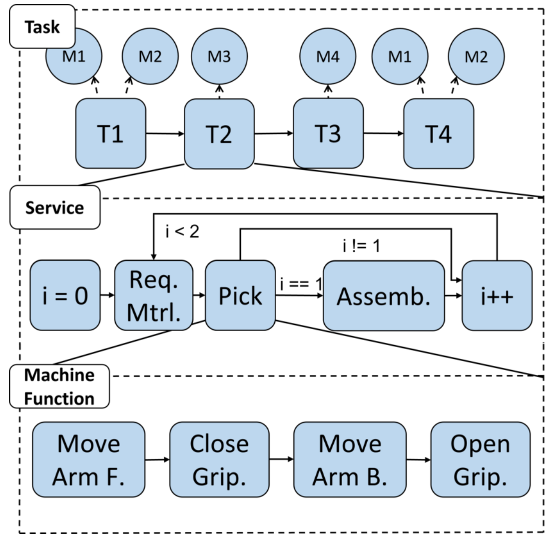

Fig. 2. An example of the proposed three-layer representation. The first layer defines the set of tasks and their allocation onto machines. The second layer depicts "services" specified in a control flow graph implementing the task *T2*. The third layer outlines machines' functions implementing the *Pick* a service.

such as predictive maintenance, and then by extending and mathematically formalizing production recipes, the structure of a production plant, and machine services. This will enable both the automatic generation and optimization of production recipes given a production line, and a final product to be produced. Furthermore, all these works will also be validated in the Industrial Computer Engineering (ICE) Laboratory: a research facility of the University of Verona[1], equipped with a fully-fledged production line, governed by a commercial monolithic MES. The line consists of state-of-the-practice machines comprising two 3D Printers, a Quality Control Cell, a collaborative Robotic Cell, a subtractive Cell, a functional testing Cell, and a vertical warehouse. Furthermore, all the machines support all the industrial standards available on the market.

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