Overview of the PhD Project: Agile Control Architecture for Reconfigurable Manufacturing Systems
Bringing Flexible Manufacturing to the Next Level

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1 INTRODUCTION

The manufacturing industry is changing. This change is driven by several developments, including technological changes, customer expectations, and paradigm shifts in the manufacturing industry itself. Most notable developments in technological changes are 3D printing, which can be applied to different fields, including metal printing and the possibility to quickly produce prototypes. This gives the possibility to quickly automate the manufacturing of shapes that were originally manually crafted. Considering the paradigm shift, there are two large changes which can be seen from the business and engineering perspective. The business is organizing their company processes to be able to quickly adapt to market changes, providing quick product to market abilities, in manufacturing this is called 'Agile Manufacturing' (Gunasekaran, 1999). From a (mechanical) engineering perspective machine builders are designing their machine to be modular, with the goal to standardize parts so they can easily be replaced, reused, or reconfigured (ElMaraghy, 2005). The change can also be seen from the customer point of view. While once you only had one choice of the color of a car, you can now choose your own color, bluetooth kit and wheelset.

With 3D printers the diversity and opportunities to create specific parts will likely increase dramatically. This could be a huge boost to creativity, where people can print their own glasses, or spare parts for their classic restored car. This might create new markets for automated mass customization.

2 RESEARCH OVERVIEW

In this PhD project the goal is to research the use and implementation of new technologies to create a shorter time to market for automated manufacturing of new products. This should enable the possibility to especially automate the manufacturing of 'high mix, low volume' products that could originally only be done (cost-efficiently) by manual labor. To make this possible, a new way of manufacturing has been introduced, called 'Grid Manufacturing' (Puik and Moergestel, 2010). Grids use a set of reconfigurable machine systems, called 'equiplets' to offer a diversity of generic services. In this concept an equiplet is a simple, autonomous low cost platform that is highly standardized so it can easily be reconfigured to offer new manufacturing capabilities. Hence, equiplets are able to quickly adapt to new market needs.

The concept of Reconfigurable Machine Systems (RMS) (Koren and Shpitalni, 2010), like equiplets, have been researched before. However, focus has mainly been on the modularity of the hardware. In the field of Agent Technology, software has been used to create flexible logistics, that are also required for grid manufacturing. This introduces problems whereof some have been widely researched, like the job-shop problem. However, the use of agent technology on a lower level, like hardware control and direct industrial use has been very limited. Hence in this PhD project it was chosen to take a bottom up approach where autonomous systems will be used to create flexible manufacturing systems for equiplets and grids. This quickly introduces many fundamental and practical problems, e.g., capability descriptions of the hardware, influence of reconfiguration to Supervisory Control and Data Acquisition (SCADA) systems. This introduces new varieties to scheduling problems. Instead of optimizing scheduling, resources could be changed or added to improve efficiency.

The research project is built around the concept of grids and equiplets. In this concept all systems have a virtual counterpart, i.e., agents to represent them. Basically the manufacturing process is completely dy-

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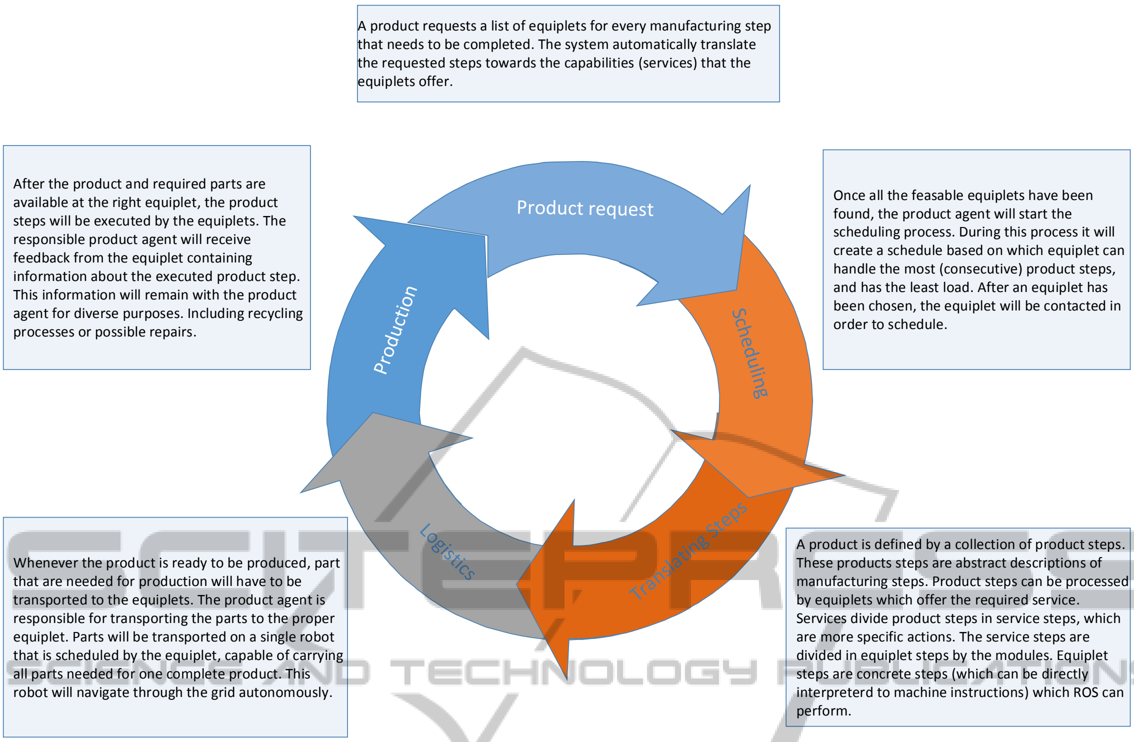

Figure 1: Basic representation of one step in the manufacturing process.

namic. Figure 1 shows the basic process of how one step in the manufacturing process is performed.

3 OUTLINE OF OBJECTIVES

The objectives are to create a fully functional grid using a limited amount of equiplets. These will be used to answer the following research questions:

- Which technologies can be used to enable flexible manufacturing?
- What are the properties of a hybrid platform and are these properties compliant for industrial use?
- Can the intelligent behavior of autonomous systems be compliant with current or future industrial safety regulations?
- How can you describe a product of which its manufacturing process is independent of specific manufacturing hardware?
- Is it possible to change (add/remove/reconfigure) manufacturing resources in an active manufacturing environment? Which effects will this have on the overall system.
- Which technologies can be applied effectively to minimize the installation and setup times for the software of reconfigured manufacturing machines?
- Is it possible to effectively use simulation / emulation to plan reconfiguration actions in the future that improve the overall efficiency of a grid.

These research questions are, as mentioned before in the introduction, meant to achieve a shorter time to market. This is achieved by providing the ability to cost-efficiently use automated manufacturing for medium product quantities. Specific main objectives are the creation of a hybrid architecture with both the performance, safety and stability characteristics with industrial specification. Secondly, systems should be autonomous, so disturbances within the grid will lead to minimum problems to equiplets. The equiplets themselves should be reconfigurable with a number of modules that can automatically be reconfigured. The grid itself should also be reconfigurable by adding or removing entire equiplets with minimum disturbance to other systems in the (partly active) grid.

Secondary objectives are the research of scheduling and optimization routines for the grid. This might involve a study of distributed (heterarchical) versus centralized (hierarchical) scheduling and investigation of the general business case.

Besides these objectives other researchers related to this project have specific objectives including the research of cost efficiency of grids (Puik et al., 2011), product/process modeling of reconfigurable manufacturing systems (Puik et al., 2013) and several aspects of the product agents, including scheduling, recycling and repair (van Moergestel et al., 2013).

4 STAGE OF THE RESEARCH

Currently most of the project has been focused on the implementation of several prototype equiplets that can be used to create the grid. This involves both hardware and software developments; since this is a multi disciplinary endeavor, literature is still being studied in parallel with the development process. The results of this study will be used for the experimental design of the deliberative systems that are part of the the grid software architecture.

The hardware of several prototype equiplets have been completed, with a diversity of hardware modules. Including a 3D printer module and a deltarobot for pick and place actions. Figure 2 shows a prototype equiplet platform and model, configured with a deltarobot pick and place module for assembly purposes.

To be able to conduct research a proof of concept hybrid software architecture has been created that combines both a reactive and deliberative layer using agent technology. This platform is being used to research several essential topics, including:

- The Hybrid architecture based on Robot Operating System (ROS) for hardware control and Multi Agent Systems (MAS) using Java Agent DEvelopment Framework (JADE)
- Automatic Translation from a product description to hardware instructions
- Reconfiguration of equiplets
- System behavior and safety of reconfigurable machine systems
- Resource Management in a (changing) Grid
- Grid Simulation and optimization

The first topic, hybrid architecture is nearing completion; this was based on a study of the requirements which have been published (Telgen et al., 2013a). As a result of this the architecture shown in Figure 3 was developed. This platform is divided in three layers. The Modules layer controls the hardware on the lower level. Modules are sensors or actuators which require specific software. On the equiplet level the modules are controlled by an equiplet node. Nodes are separate processes in the Robot Operating System, a specific software framework for robot software development (Quigley et al., 2009). On an equiplet level the equiplet node takes commands from a blackboard that is controlled by an equiplet agent. On the ROS level there are also some smarter processes, like computer vision. These are conducted on the ROS level to ensure their performance. Data that is perceived by the sensors is modeled in the environment node. The grid level encompasses all systems that are common for all equiplets. It has several databases which can be used to acquire specific software for new configurations and to store logistics information. Product agents are mainly set on the grid layer to negotiate with multiple equiplets, depending on the required manufacturing steps that they need to perform. The process of the negotiation has also been studied using simulations and published (van Moergestel et al., 2012).

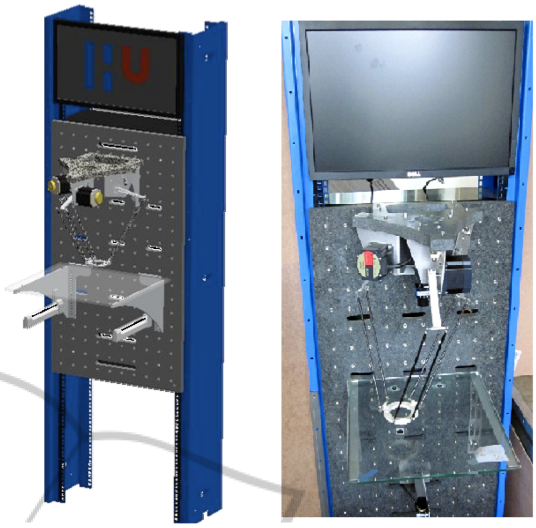

Figure 2: On the left of an equiplet with a deltarobot and glassplate working area module attached. Right a real equiplet prototype with a deltraobot module and a glassplate working area that is used to observe with a computer vision system to localize parts.

5 RESEARCH PROBLEM

The main problem of the research project is how to efficiently create reconfigurable systems that can be, flexible, autonomous, safe, efficient, cooperative, predictable, low cost, fast, and easy to use. The first problem in this task is to discover how to combine the reactive layer that controls all hardware with a deliberative layer that controls all higher processes. This will guarantee both the performance required for hardware control and more intelligent behavior that is necessary for the decision processes on higher layers, that have to deal with the flexible nature of grids.

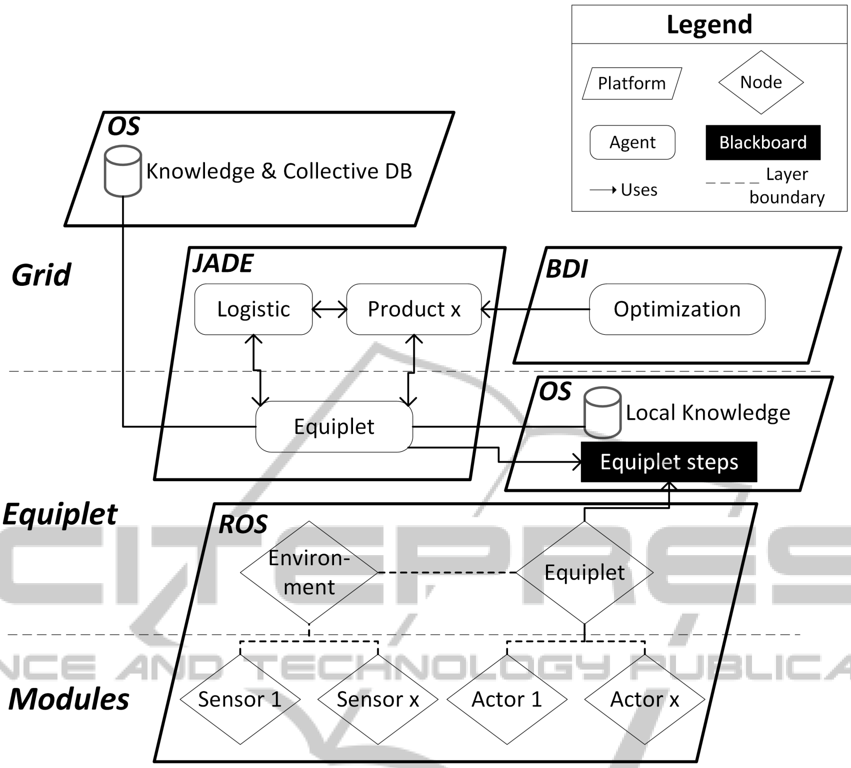

Figure 3: Overview of the basic hybrid architecture using Robot Operating System and a Multi Agent System based on JADE.

Once a proof of concept architecture has been designed, the next problem will be to make the systems reconfigurable. This creates several problems, since one of the goals is that reconfiguring hardware will not require any new software coding and/or compiling. To make this possible the systems should be easily configurable and be able to automatically load new software modules, like plug and play devices in a PC. However, in contrast with PC's, machines are less standardized and have actuators that can also have a high dependency on each other, e.g., a gripper placed on a robotic arm changes the working area of the actuator, which has an impact on safety behavior. Also some actuators require physical calibration. As such a large amount of knowledge is required to support the automatic reconfiguration of the software for reconfigurable machines.

Once reconfiguration is possible, capability and resource management become important. Products need to know which steps can be reconfigured at which equiplet. Since equiplets can be reconfigured, the manufaturing resources can be changed during runtime. This gives a variation on the job-shop problem, which in its static form is already NP hard. However, in this case the resources (shops) can be changed to optimize the manufacturing (jobs) in the system.

Besides these main problems, there are also several practical and interesting problems, including how to dynamically find objects (using computer vision), logistics (connecting to ERP systems and transport logistics between equiplets), scaling and stability issues. As far as feasible within the time constraints, these problems will be taken into account.

6 STATE OF THE ART

Several aspects can be considered state of the art. To discuss this matter, this chapter shall give an overview of comparable work and the differences with the current research project.

Paulo Leitã has published an extensive survey of agent technology in manufacturing in 2009, he clearly states in his conclusion that traditional manufacturing control systems are adapted case by case. Hence, it is expensive and time consuming to develop, maintain and reconfigure. A large aspect of this is the limited ability to deal with disturbances of any kind. As such, he stresses that traditional manufacturing control needs to be renewed with emerging technologies to create agile and reconfigurable architectures. In his survey he also mentions that control systems in the context of reconfigurable manufacturing systems are extremely rare and usually restricted in its implemented functionalities. The adoption of these technologies in industry are therefore very limited (Leitão, 2009). Because of this it is important that in the current research project real functionality can be shown to industry to prove its effectiveness. This had led to the actual development of prototype systems that are shown to industry [1].

(Heintz et al., 2007) and (Järvenpää and Torvinen, 2013) discuss some topics which are related in this research. Heintz et al. discusses the sense-reasoning gap, applied to UAV's where abstract information is step by step deliberated to specific information. Järvenpää shows how to match product requirements with system capabilities of the manufacturing equipment. In our research we add both these principles and take it further to use the capabilities of the machines to automatically translate these to specific instructions that control the hardware that will be used. This translation process will be conducted in real time and does not require compilation of code. Instructions are communicated directly by the agents to the lower ROS level (Telgen et al., 2013b).

Schild and Busmann are well known for their work in using agents in manufacturing. Especially the 2000+ production system[2] is of interest. This system was able to manufacture a number of variations of cylinder heads and has been in active use at a Mercedes-Benz engine plant. In this system it was possible to change some programs for each variant and to use a flexible transportation system. This system utilized Computerized Numeric Control (CNC) machines. While this system was successful, it was also expensive and limited to CNC's machines that could automatically switch tools. So far, the 2000+ system seems to be closest to our goals, it was decommissioned in 2005 after the product's life cycle was ended. No new systems were setup, mainly because of the high costs and difficult business case.

In contrast with 2000+, our research project focuses on even more flexibility, to such extend that machines can offer a wide variety of products within a grid. Basically this is achieved by lowering the cost of standardized platforms and make them offer one single simple service. These services have a large diversity, since the machines offer generic (non product specific) services. Including computer vision camera and assembly operations. Reconfiguration aspects therefore become more important, since there are a wide range of capabilities. This offers a range of problems as mentioned in the research problem chapter.

While these referrals show how to place this project as state of the art in comparison with other work there are also general changes in the market that enable this research. For example the need for mass customer-unique products, that is fueled by 3D printer technology, and the return of high-tech manufacturing to the western countries are an important stimulant for this research project.

7 METHODOLOGY

This research will be conducted at an applied university. As such the practical feasibility and therefore valorisation at the industry is considered to be extra important. Hence, an entire grid will be completed, including hardware and software which will be used as a proof of concept for a grid using equiplets. This influences the research, since it becomes harder to isolate individual aspects of the work, because all results have to be placed in the larger context of industrial flexible manufacturing and can not be limited to a simulated model. At all times all results should be validated in a practical context of the entire system. Hence, this project is given an experimental character that has to be validated with empirical data. While this is possible for some research aspects, the large scope of the project might make it hard to use quantitative analysis of all aspects. As a result, the scope will need to be made smaller by deciding on some aspects using qualitative methods. An example of this is how the basic platform for the software of the equiplets was chosen (Telgen et al., 2013a).

8 EXPECTED OUTCOME

On a practical level the main goals are to make a small grid with a number of reconfigurable equiplets which can demonstrate the proposed technologies. This includes reconfiguration, safety aspects and the automated scheduling and instruction generation. This proof of concept will be analyzed to proof its effectives to industry. Formalization of the agents, ontologies and the automated translation are most interesting from a scientific perspective. However, the practical appliance and testing of the hybrid architecture are also considered essential to prove how these kind of technologies can be valorized.

Besides the physical creation of a small grid there is the development of a full simulated grid, where

[1] Demos of the current project are shown at the precision fair every year: http://www.precisiebeurs.nl/intro-en-us/ last visited December 2013

[2] 2000+ production system: http://www.stefan-bussmann.de/en/agents/p2000p.html last visited December 2013

hardware will be emulated to be used in a fully functional MAS that controls all higher level aspects. These can be used to conduct several experiments like optimization through the use of reconfiguration and other logistical aspects like error behavior, etc.

9 CONCLUSIONS

This article gives an overview of the topics in this of the PhD project named: 'An Agile Control Architecture for Reconfigurable Manufacturing Systems'. It introduces the concepts of equiplets and grid manufacturing and shortly describes the involved problems and goals. Some aspects, like general concepts, the hybrid architecture and automatic translations of manufacturing steps to instructions have already been published. However, many aspects still require more research. Especially the metrics on the full architecture will provide more insight in the effectiveness of this approach. A big challenge is using the relatively new technologies and prove their suitability for real industrial use. However, if this can be (partly) achieved this could potentially have a high impact on industry.

On of the risks of this project is the large scope. Specific research questions are limited by the large amount of possible implementations. The implementations have then to be tested in a complete live system, running several safety and practical limitations that might influence the metrics. While this is a challenge, it is expected that this research will be useful for new research and industrial projects in the future.

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