Adaptive Autonomous Machines - Requirements and Challenges

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Abstract. In mechanical and plant engineering, the general challenge is to achieve flexibility in order to process changes in the requirements or operating conditions of a machine on the site of the plant operator. Changes to the machine and its configuration require the operator to work together with the machine builder (or plant constructor for several machines) and, if necessary, with his suppliers, which requires time and effort due to communication and delivery routes. Hence, an autonomous acting machine or component that deal with needed changes through automatically triggered adaptations would facilitate this process. In this paper, subtasks for constructing autonomous adaptive machines are identified and discussed. The underlying assumption is that changes of machines and components can be supported through configuration technologies because those handle variability and supply automatic derivation methods for computing needed changes in terms of machine and component updates.

1 INTRODUCTION

In recent years, the demand for the industrial production of small quantities has increased steadily. Whereas in the past larger industrial plants were designed for the production of large quantities of exactly one product whose parameters did not change, today the possibility of fast, flexible adaptation to changes in product lines is becoming increasingly important. While an adjustment of the machine settings is often sufficient for minor changes, larger adjustments require a modification of a machine by the machine manufacturer, or even changes of a complete production plant. For this purpose, the dependencies of individual plant components must be taken into account, e.g., the use of a stronger motor at one point would possibly also require the use of a drive shaft that can withstand higher torques. If individual plant modules can be configured to give a higher or lower speed, instead of a higher throughput other modules could be enabled to achieve a higher accuracy.

In this paper, we present first considerations for enabling machines or components to themselves start adaptations of their configurations. Firstly, we discuss the current process in plant engineering for adapting machines (Section 2). In Section 3, we provide an illustrating example and in Section 4, we present our concept for autonomous adapting machines and in Section 5, we discuss main challenges for realizing such machines, especially in respect to configuration tasks such as reconfiguration.

2 CURRENT SITUATION IN PLANT ENGINEERING

The component manufacturer has developed products whose product features can be configured in a variety of ways to cover a wide range of missions [7]. For a power unit, such product characteristics are: Torque, rotary speed, type of sensors, type of actuator, mechanical interfaces, electrical interfaces, control characteristics, functional characteristics, but also something basic like color. These have to be considered as drive systems, which in some cases have to be understood as poly systems, since there are central components, such as the power supply, or a controller, which specifies a coordinated movement, such as in robot kinematics.

The interactions between the power unit components of a drive axle or a drive system, starting with the connection to the control system up to the driven components or the mechanics, can be very extensive, so that the machine builder is dependent on the knowledge of the component or solution supplier. The development of suitable drive solutions is therefore usually carried out in close cooperation these days. On the other hand, machine builders want to reuse their developed results wherever possible, which forces them to modularize their machine solutions. Machine modules are then defined which combine one or more drive axes or drive systems.

A general overview of the current plant engineering process is given in Figure 1. After the mission and the classification of the client's requirements, a concept is created that may include existing solutions. Requirements for such solutions can be functional (movements, production steps) and constructive characteristics (dimensions, interfaces such as connecting elements etc.). When deciding on a solution, various aspects have to be taken into account. Some lead to severe restrictions, others are free, and still others have consequences for other solutions or components. If automation or partial solutions are available (selction of partial or automation solutions), these can be integrated into a machine solution. Integration refers to function, design, parameterization, wiring, but also to organizational issues such as spare parts inventory and documentation. The planned mechanical design can be verified by means of a simulation (simulation). Once a decision has been made on an overall solution, the electrical, pneumatic and hydraulic design (construction) is carried out. This is incorporated into the development of machine control and operation and can be put into operation virtually (virtual commissioning). After the customer has placed his order (order and logistics) on the designed solution, the montage and initial commissioning with

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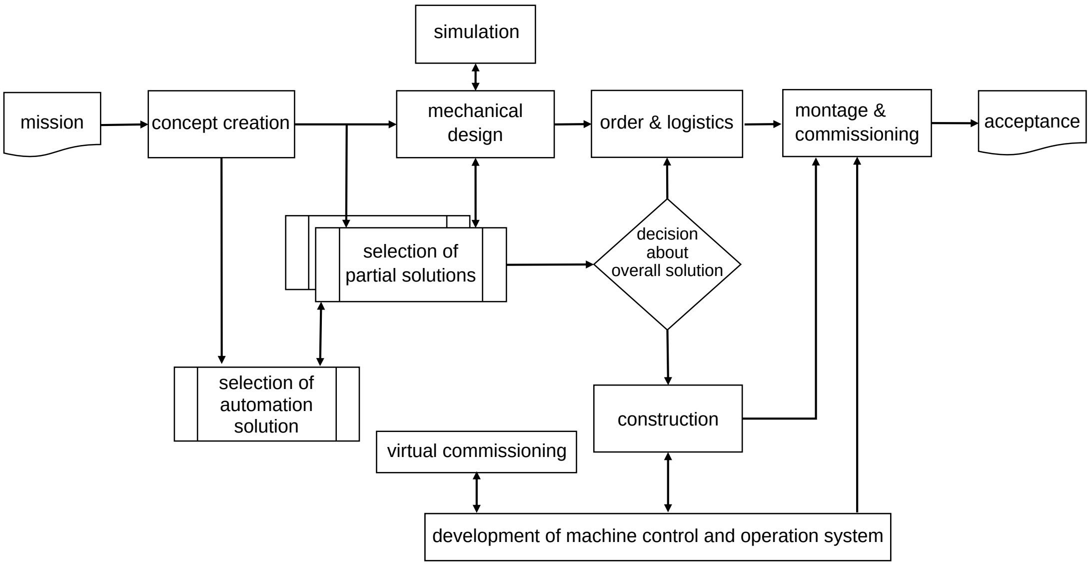

Figure 1. Current plant engineering process

the commissioned construction and machine control and operation will take place. The process concludes with customer acceptance.

3 EXAMPLE FOR AN AUTONOMOUS AGENT

Our goal is to deliver not only a machine (consisting of several components) or a component to a customer, but also so-called autonomous agents. These have the task of monitoring the machine/component and adapting it to requirement changes. The machine/component together with the autonomous agent forms the autonomous adapting machine. If changes are made in the machine, the autonomous agent also changes the description of the machine. The agent can be regarded as an IT system for changing the machine, whereby the agent, i.e. the IT system, also adapts itself dynamically.

Figure 2 shows the interaction of the autonomous agent with the machine and its environment in a scenario with independent adaptation to new or changed requirements, where only one agent and one machine are shown.

Since configuring a plant is a common example that illustrates configuration processes, the following are examples of the individual elements in Figure 2 based on a plant engineering configuration. In addition to the main components (drive unit, fan, running gear, rack feeder, sensor, picker arm, etc.), a classic plant can have fans for cooling the internal case temperature or individual components. We assume that a plant is already configured in a certain way (B) to solve a certain task (A). Using sensors, an autonomous agent could now determine that the system load is slightly higher than 1, which means that the plant is slightly overloaded (C1). An internal list of suitable components (C2) could show that it is possible to replace the drive unit with a more powerful model. However, we assume that the drive unit delivers weaker performance than possible due to overheating. Since this information is also made available via sensors (C1) to the agent, he will decide (C3) to optimize the cooling instead of changing the drive unit. Since the installed fans already deliver the full performance, a solution could be to install another fan, as far as the case offers this possibility, which would also be ensured by checking (C2). Alternatively, the manufacturer could also offer an improved fan with higher cooling capacity (E), which would replace an installed one. While monitoring (D) ensures that changes to a plant do not adversely affect plants placed nearby, virtual verification (C4) will check whether the improved cooling capacity will be sufficient even under summer factory workshop temperatures and if proper cooling is sufficient to lower the system load below 1. Adaptation planning (C5) means determining that shutting down the plant is necessary for the given changes and could also determine the optimal time to do so. Both virtual verification (C4) and adaptation planning (C5) are monitored and accompanied by human experts. Finally, the change must be made (C6), which then changes the system properties (B).

4 GENERAL CONCEPT FOR AUTONOMOUS ADAPTING MACHINES

We expect that the machine is accompanied by a complete description of the currently installed (probably parameterized) components, *the configuration*. The configuration is an instance of a configuration model. The configuration model is given in machine-readable, semantically interpretable form [4]. It represents the variants of system components as well as mappings between external parameters describing requirements and components realizing those. Additionally to this configuration model a here called *action model* describes how the agent can acquire new requirements in the productive environment. This happens on the one hand by sensors, which seize the environment (e.g., pressure, temperature), on the other hand, by accesses to other systems in the productive environment (like for example other machines and the development system with the machine-builder). *Adaptation* now is defined by changing the configuration and the actual system, the machine. Changes in turn can be parameter changes, additional components, or component replacements.

The requirements are continuously determined and compared with the external system parameters of the current machine. This is used to determine which properties, parameters or functions are not fulfilled by the current configuration or solution (C1 in Figure 2). If the boundary conditions of the environment or process parameters change during system operation so that requirements are no longer fulfilled, the autonomous agent becomes active in the same way as when requirements are changed in order to achieve fulfillment of the requirements by changing parameters, configuration or solution ele-

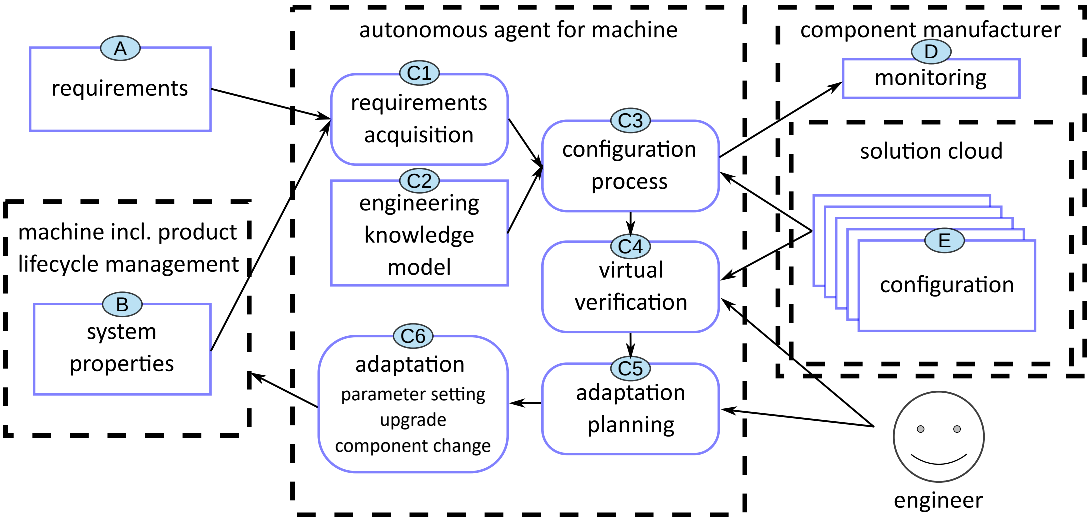

Figure 2. Scenario: independent adaptation to new requirements

ments.

The models will be delivered with the machine in order to achieve autonomy. On the other hand, it should be possible to extend the models by using remote knowledge structures at the component manufacturer (E). This solution cloud contains a lot of solutions that the agent cannot calculate on his own. This can be the case with complex calculations, innovations regarding other components or integration tasks. These descriptions are available as configuration models in a form that can also be evaluated by the autonomous agent.

In addition to access the set of solutions, the autonomous agent also has an engineering knowledge model (C2) that can be used to determine solutions. This knowledge model contains different reusable means such as component, machine and context models, procedures (e.g. planning and design methods), different libraries of solution ideas (descriptions of earlier solutions together with their properties and evaluations in the form of models) and solution knowledge (such as heuristic elements or regular information).

In some cases, the autonomous agent can find a solution that meets the requirements (C3). This is tested and realized e.g. by parameterizing or changing the configuration of the system. In other cases, the autonomous agent proposes solution variants that require additional development activities by a machine builder or an exchange of solution parts. In these cases, the autonomous agent provides the necessary information such as requirements and boundary conditions to the solution provider (e.g. special machine builder or drive supplier), which are checked and evaluated by a development engineer and then implemented.

Due to its engineering knowledge model, the autonomous agent can participate in the verification by the developer by, for example, checking the consistency of the solution, simulating processes and evaluating predictions of the behavior after the changes (C4).

If necessary, the autonomous agent is accompanied by an engineer while he applies the steps involved in implementing the solution, such as selecting elements to be replaced, changing the configuration and defining new parameters. By using the engineering configuration model with the means of finding solutions, risks during implementation are reduced by monitoring (D) the consistency of parameters and configurations at each intermediate step and applying successful procedures at implementation steps. In addition to simulation and verification, undesired emergence, which could arise from autonomous decisions, is recognized and ultimately prevented by monitoring. Knowledge-based monitoring monitors the activities of the autonomous agent. For this purpose, knowledge modeling about the possible activities of the agent as well as of the machine and its environment is used. This makes it possible to analyze and reflect on actions while the agent is performing them and thus to recognize unsafe actions and interactions. The simulation shows on the other hand the system's adapted behavior by means of a simulation model, which processes the changes of the system behavior.

The autonomous agent involves various solution component vendors in order to obtain additional or new solution elements and new configurations. These new solution elements can also be deployed after the component vendor has analyzed the new requirements and then developed a new component - which of course takes some time.

Several solution agents based on our concepts carry out self-organization in the sense that solution knowledge is brought together both at the (special) machine manufacturer and at the supplier of solution parts such as drive solutions in the search for suitable solutions. There is also interaction with domain experts who contribute further engineering knowledge or make decisions.

Some examples of scenarios that an autonomous agent can support are briefly listed below:

Scenario 1: Increasing the load on a machine.

- Examples: Higher number of cycles than previously planned, larger masses than previously planned.
- Possible solutions of the agent: A different machine model is proposed, a larger engine is proposed.

Scenario 2: Changing the requirements of a machine.

- Examples: Different environmental conditions, higher accuracy
- Possible solutions of the agent: Other devices are proposed, a reduced machine speed is proposed, another position sensor is proposed.

Scenario 3: Change of the solution offered by the supplier.

- Examples: A new low-maintenance gearbox or a new, more powerful conveyor module is available.
- Possible solutions from the agent: A redesign of the machine or the line is proposed and argued (costs, benefits).

5 CHALLENGES FOR CREATING AUTONOMOUS ADAPTING MACHINES

We identify following technologies for realizing autonomous adapting machines. Figure 3 depicts a summary of the proposed knowledge separation. The configuration model of a machine represents all variants of the machine and its components [2]. The configuration model (depicted as *CM-C*) is distributed, i.e., the autonomous agent contains one part (CM_A-*C*) of the configuration model and the cloud of the component manufacturer another part (CM_C-*C*). CM_A-*C* contains the variants that are used and included during the time the machine was manufactured. It is updated if the machine is adapted. Considering that only some components supplied by a component manufacturer constitute a machine, CM_A-*C* has to be extracted from the configuration model that represents all components of a manufacturer. CM_C-*C* changes over time if the component manufacturer develops new components. Besides the configuration model the autonomous agent contains the actual configuration of the machine (current running hardware and software of the plant), i.e., an instance *CM-I* of the configuration model. Besides the configuration model *CM-C*, a requirement model *RM* will describe all possible requirements the components of *CM-C* shall supply [6]. Additionally to the requirements and the configuration model, we consider here a sensor model as a further artifact for structuring the knowledge of an autonomous agent. The sensor model *SM* represents all sensors that can acquire values about states in the environment [3, 5]. This model also entails knowledge about thresholds for deriving qualitative values about the world external to the machine. Those are mapped to the *RM* for deriving possible requirements *R* the machine has to fulfill [5, 6].

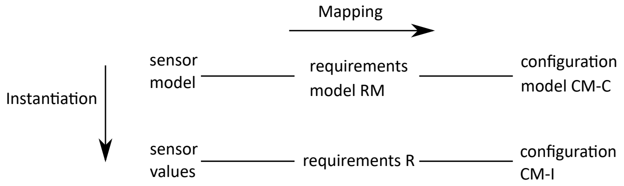

Figure 3. Separation of models for sensor, requirements, and component knowledge in general (upper row) and for one machine (lower row)

By representing all those models and mappings as well as the identified new sensor values in a reasoning tool, a new configuration can be inferred with commonly known technologies [4]. Monitoring and verification of intended adaptations are further tasks which will apply simulation technologies and high-level monitoring of (here intended) activities [1]. The needed adaptations (e.g., component changes or updates) have to be identified, e.g., by comparing the original configuration and the adapted configuration. Furthermore, necessary planning actions have to be derived from a planning domain and finally executed [8]. All those technologies have to be combined in an architecture for autonomous adapting machines which includes decision about local and remote computations [8].

In a later step of our research, a further challenge comes into play when interactions with other machines that become part of a collaborative system as part of a changed manufacturing process are considered. Collaborative systems in manufacturing processes are also considered in the area of Industrie 4.0. However, in this field the focus is to automatically setting up collaborative cyber physical systems for production, through adaptive systems, as we are considering here, the adaptation comes as a further challenge into consideration. In the field of Internet of Things (IoT) similarily the processing of senor data is considered. Their combination with configuration tasks were also discussed by others, e.g. [3, 9].

6 SUMMARY

In this paper, we propose the use of configuration technologies not only in the beginning of a product lifecycle, but also during runtime of machines in production. Knowledge about variants and dependencies, as well as reasoning methods known from the area of knowledge-based configuration can support the adaptation of machines. However, additional technologies, such as sensor evaluation, as well as adaptation planning, monitoring and simulation have to be considered. During our further research we will identify concrete application scenarios for guiding the research in the direction of autonomous adaptive machines.

ACKNOWLEDGEMENTS

We would like to thank the referees for their comments, which helped improve this paper considerably. The paper is supported through the project ADAM granted by the Federal Ministry of Education and Research of Germany.

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