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Reuse of modules for mechatronic modeling and evaluation of manufacturing systems in the conceptual design and basic engineering phase

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Abstract: In the engineering of automated manufacturing systems a lot of effort is spent on the conceptual design and basic engineering phase. In this paper a methodology of modeling and evaluation of system concepts, based on mechatronic modules to support and ensure the decisions made during these phases, is presented. This methodology facilitates the design of such a system by integrating the reusable mechatronic modules in the engineering and simulation process. Therefore, the adaptation of engineering modules for their reuse within the simulation is described. The reuse of modules aims at reducing the time of modeling and evaluation of the resulting blueprints by machine simulation.

Keywords: Modularization, Development and Design, Automated Manufacturing Systems

1. INTRODUCTION

Manufacturing systems are nowadays solutions, which are adapted to the specific requirements of the customer and no more standard machines which are designed, manufactured and sold regardless the production process of the customer. Therefore, the engineering of such systems must be adapted to these conditions. The continuous adaptation of the manufacturing systems to changing requirements causes that the engineering time has to be shortened in order to react quickly and flexibly. Moreover, the systems cannot be physically tested in detail during the engineering, which leads to an increase demand on simulation. One approach to reduce the engineering time and increase the quality of the machine blueprint is to model and evaluate manufacturing systems based on the reusable objects. The methodology presented in this paper aims at:

- Reduction of engineering and simulation time by systematical reuse of modules
- Integrating the reuse of modules in the process
- Adaptation of the modules to machine simulation

The methodology is illustrated by the example of an assembly system which is described later on. The improvements in the engineering process based on simulation of the manufacturing systems and the reuse of modules will be presented in this paper. An improvement is the reduction of time in the conceptual design and basic engineering by reusing modules in the modeling of alternative concepts and in the simulation. Moreover, the performance of the modeled concepts is ensured by the evaluation, by the pre-selection and the simulation results in an early stage of the engineering process.

2. STATE OF THE ART

A key challenge of optimization of engineering is to reduce the engineering time, to be able to react quickly to changing requirements (Alvarez Cabrera et al., 2010). Furthermore, an analysis of information flow in engineering proved the importance of interfaces between the disciplines (Behncke et al., 2011). Possible approaches are proposed with consideration of the specification of requirements and modeling the relationships between the disciplines (Li et al., 2012). Some aspects of the cooperation across mechatronic disciplines in engineering are depicted in different tools (Anacker et al., 2011). Furthermore, tools have been developed to allow the exchange of information between the disciplines (Brecher et al., 2010; Draht et al., 2011; Moser et al., 2012).

One interdisciplinary tool is the machine simulation for the validation of mechatronic machine concepts. The machine simulation is used for the control test and virtual commissioning. With simulation early engineering steps can be reviewed, concepts can be compared and early errors such as design errors can be detected. In subsequent steps the control software can be tested and pre-optimized before commissioning.

A basic approach of module-based engineering is described by (Weyrich et al., 2012). This approach enables the modeling of a blueprint of a new manufacturing system based on reusing mechatronic modules in the early stages of the engineering. One way to systematize the modules is to assign them to functions (van Beek et al., 2010).

The risk of errors in the blueprint of manufacturing systems is reduced by the integration of knowledge in this phase of the basic engineering phase (Rimpau et al., 2010). The reuse of modules and related knowledge is described by Fay et al. as an opportunity of making systematic improvements on engineering (Fay et al., 2009). In addition to these approaches for modeling of manufacturing systems, there are a variety of approaches and methods for modeling of standardized products from a known set of modules (Vogel-Heuser, 2009).

Alternative approaches to Mechatronic Engineering deal with design pattern and mechatronic units (Lüder et al., 2011).

The components-based modeling of manufacturing systems can be supported by modeling languages (Atkinson, 2002). Furthermore, some approaches can be transferred from the field of object-oriented modeling of control to the engineering (Vogel-Heuser et al., 2011). Here, the handling and the inheritance of behavior and properties of the objects are important (Bonfe et al., 2006). The module selection should be evaluated to compare different blueprints in the modeling of new manufacturing systems (de Lamotte et al., 2006).

An important prerequisite for the modeling of new manufacturing systems is the reusability of objects (Feldmann et al., 2012). Thereby, the granularity of the components must be chosen in an appropriate manner (Maga et al., 2011). The reuse of existing models and sub-models are also applied to increase the efficiency and economics in machine simulation projects (ElMaraghy et al., 2012). Simulation models are often developed only for a single application and for a particular purpose. New requirements demand that the simulation models have to be reused for different purposes along the engineering and machine life-cycle. Therefore, it is necessary to create different variants of simulation models easily, e.g. via automated methods (ElMaraghy et al., 2012).

The application of reusable models is another approach to reduce costs in the simulation modeling process. In VDI guideline 3633 the partial and complete reuse of simulation models is recommended, but specifications of the modules properties are not discussed in detail. Actual modularization approaches demonstrate the use of simulation modules (Weyrich et al., 2011). The simulation modules are based on the mechatronic engineering data as circuit diagrams, fluid plans and 3D-CAD data. A special benefit of simulation modules is the ability to integrate this approach into current engineering processes (Schob, 2012). Those modules are also used for the automatic or semi-automated creation of simulation models.

3. METHODOLOGY

New products, new technologies and changing requirements are possible triggers for the engineering of new blueprints or changes in existing manufacturing systems. Different concept versions have to be compared in an early stage of engineering, in order to develop or to change manufacturing systems quickly based on this trigger. As a result, errors and the subsequent costs can be avoided. In the following, the procedure of modeling, ensuring and evaluation of alternative blueprints is explained in more detail.

Many data and information about the components and modules are required for the modeling and simulation of the resulting blueprints. The reuse of modules and related information is one aspect for the systematic improvement in engineering (Fay et al., 2009). Therefore, module-based manufacturing systems are configured according to the requirements of the manufacturing process in the method described. The methodology of mechatronic modeling and evaluation of manufacturing systems is based on the reuse of mechatronic modules. Figure 1 illustrates the process of mechatronic modeling and evaluation.

I. Existing manufacturing systems are modularized to set up a knowledge base with adaptable and reusable engineering modules. These modules are the basis for the modeling and they are systematized by an assignment to functions.

II. The developer is able to select appropriate modules based on a process description based on these functions. Various blueprints of the system to be engineered result which meet process description.

III. These blueprint are compared by an evaluation of the feasible cycle times. In addition, the basic functionality is carried out by means of simulation tools.

IV. The selected blueprint is elaborated into a detailed concept of the manufacturing system.

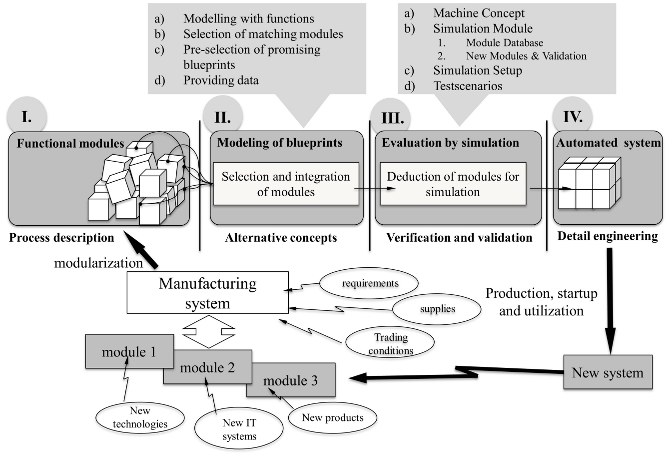

Fig. 1. Methodology of mechatronic modeling

The selection of the blueprint to be engineered is based on static information by a pre-selection from a database (e.g. as energy consumption, cost and reliability) and the information based on simulation results (e.g. cycle time, possible collisions). These information are available at a very early phase of the engineering process.

3.1 Modeling of a manufacturing system

In a first step, the manufacturing process to be realized has to be modeled with a specified range of hierarchical, solution-neutral functions to create different concepts of the manufacturing system. The engineering modules are interchangeable, since several modules perform the functions in the process description. As a consequence, various possible blueprints of the manufacturing system can be modeled. Alternatives of module combinations must be evaluated to select the variant which performs the manufacturing process best. This evaluation is enabled by the simulation of the blueprints. For this, the relevant data of the alternatives are provided for the simulation. Engineering objects, such as those used in the *Open Engineering Service Bus (OpenEngSB),* or other tools for exchanging data are one possible exchange concept (Moser et al., 2012).

a) Modeling with functions

Basis of the modeling are the reusable engineering modules. These modules are selected from a knowledge base during the modeling process. Existing production systems were modularized to build up this knowledge base. The aim of modularization is to increase the reusability of modules. Thereby, the engineering modules should be as comprehensive as possible, in order to achieve significant benefits from the reuse. The identification of the modules in several manufacturing systems is one way to ensure the reusability. For this, the size of the modules is adapted and the elements of the production systems need to have a uniform granularity. Some engineering modules are determined in the modularization, which include, for example, the control and security features. These modules are split into function specific engineering modules. As a result these modules are distributed, so they could easily be reused in the modeling of new manufacturing systems.

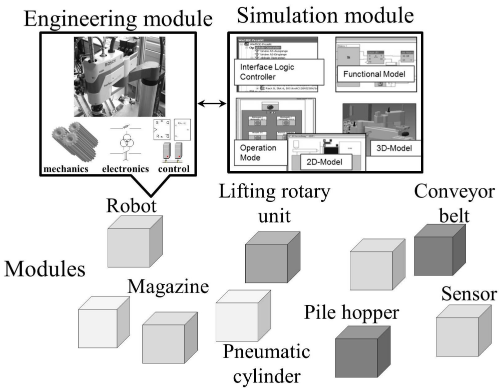

Fig. 2. Engineering and simulation modules

Many data and information about the components and modules are required for the modeling and simulation of the resulting blueprints. Therefore, module-based manufacturing systems are configured according to the requirements of the manufacturing process in the method described.

Appropriate engineering modules and corresponding simulation modules (Fig. 2) are selected based on the functional description. With this, variant combination of modules might be created. These module combinations are provided for the simulation to obtain a detailed analysis and evaluation. Engineering modules which meet the functions of the process description are selected from the knowledge base. Thereby, each function can be fulfilled by a huge number of modules.

b) Pre-selection of promising blueprints

Promising combinations of engineering modules are pre-selected based on a first, static evaluation of these modules with characteristic values. Thus, not every possible combination must be simulated. The data of the prospective combinations including simulation models are provided in the connection for the simulation. The performance of the engineering modules is described as a cost function to select promising blueprints from the large number of possible combinations.

Consequently, the aim of the pre-selection is to select the module combinations with the minimal sum of the performance ratings. This cost function consists of an energy assessment, a cost assessment etc. The functions are based on the experience of further machineries. Concept variants can be compared based on these assessments by the cost function. Here, the most important requirements, such as the quantity to be produced and the material to be processed will be considered. The cost function is a rough comparison of the concept variants. Simulation is necessary to determine more accurate information on the performance of a system. Therefore, in the following the adjustment of the engineering modules to the requirements of the simulation is presented.

3.2 Evaluation by machine simulation

The machine simulation is used to generate detailed and validate information of the manufacturing system concepts. Therefore, the simulation models for the individual tests are also based on reusable simulation modules. The process description of the manufacturing system along with the engineering modules and their engineering data affect the identification and implementation of these simulation modules.

Ideally the simulation modules are exactly identical to the engineering modules, but simulation specific aspects for the identification have to be considered. Especially the goals of the simulation are of importance, as there are collision tests, tests of single modules or cycle time validation of the plant. These goals influence further aspects directly related to simulation, the simulation platform, the simulation method and the linked logic control systems.

From these aspects, additional factors are deduced for the assessment of the simulation modules as there are for example freedom of interference to other modules, scalability of the modules, configuration and scope of interface to logic control. The additional factors determine the necessary data for the simulation as well as the range and the level of detail for the simulation modules. Therefore, the simulation modules may differ in their functions and interfaces from the engineering modules.

For the identification of those modules a process has been developed. The simulation modules with their functions, interfaces and geometries should be assessed on their usability and their reusability for further simulation projects. An initial rule for the combination of functions and interfaces is that the modules should be large and functionally comprehensive. Such modules can be quickly and easily used for the creation of new simulation models. However, too large modules are complicated to scale and modify. The optimal size for the application of modules is obtained by an iterative approach which comprises the steps module identification and their subsequent assessment.

The assessment is realized by a utility analysis which is a method for the quantitative analysis in decision theory. The adapted factors mentioned above consider the established framework of the simulation project for the assessment of the modules. The associated weightings have to be determined on the importance of the different factors and should be done by a team of experts. It is important to keep the weighting for different modules equal to enable the comparison of modules with similar functionality and to assess variants of modules.

The result of the assessment is rated by a score. With a higher score increases the suitability for the simulation project and for the reuse. A module is created if a certain threshold value is exceeded. On top, there are elimination criteria that force to a re-identification process. If a single high-weighted factor is rated low or to zero, the module has to be fragmented and assessed again. Such a high weighted factor could be a special goal e.g. the testing of the single module.

After the positive assessment, the modules can be modeled and implemented in the data-base for the application and the creation of simulation models. Due to the different number of identification and assessment loops, the modules have different sizes and comprehensive functions.

The aim is to focus on simulation-related functions and geometries, consequently reducing the complexity of the modules early before the modeling. Therefore the simulation modules are divided in their functions and the required 3D-geometries. The different properties like reusability, changeable level of detail and consistence to engineering data of a simulation module can be influenced within the modeling process. Especially, the reusability and the links to other modules are important properties for the module based simulation. The new simulation modeling process focusses on reusable simulation modules and a module data-base, and differs from the traditional process to reduce the effort on modeling for a special purpose.

From the module data-base, the individual pre-validated modules are connected to the simulation model of the manufacturing system. The fact, that only few new modules have to be modeled and validated, decreases the effort on the simulation setup. The modules are used for the manual creation of simulation models. With these simulation models, individual tests for the validation of the conceptual mechatronic manufacturing systems are realized.

4. USE CASE

New products, new technologies and changing requirements are possible triggers for a new development or a change in an existing manufacturing system. If a new transport system is required to reduce the energy consumption of the manufacturing system, various alternative concepts can be quickly modeled and evaluated by the proposed approach. The kinematic simulation enables to ensure cycle times and to avoid collisions. Other simulations, such as the physical simulation and the simulation of the dynamic behavior of an entire system, can also be employed to obtain other information and evaluations of the system.

The example system described below for assembly of plugs is suitable to illustrate the approach of modeling and evaluation. For this manufacturing system new possible requirements could include for example a new plug to be assembled or the reduction of energy consumption by the exchange of pneumatic actuators with more efficient, electronic actuators. These new requirements result in a change in an existing system or in a new development. The system embodies a number of manufacturing facilities that have been specifically engineered for a production process.

4.1 Description of the example system

The components to be assembled are conveyed from two different buffers, wherein the presence of the components in the buffer is monitored. Moreover, the position of a component is tested in the function "quality control". After assembling and verifying its success by another control operation, the components are sorted for the correct assembly. Linking functions, such as conveying, are complemented in addition to the previously described process functions.

4.2 Modeling of exemplary mechatronic concepts

The assignment of the engineering modules of the exemplary manufacturing system to solution of neutral function allows the exchange of modules and thus optimizes the productivity of the system or the reduction of energy consumption. Other modules might have been taken into account in order to optimize the performance of the system.

As an example given, possible variants of the engineering modules for the function of buffering have been a magazine, a centrifugal feeder, a vibratory feeder and a pile hopper. Conveying could be realized for example by a conveyor belt, a robot, an automated guided vehicle system or a lifting rotary unit. The quality or the orientation of the components to be assembled could also be controlled by an image processing system or other optical and mechanical sensors. The assembly could have been implemented by a SCARA robot, a pneumatic cylinder or an electronic actuator. A pneumatic cylinder, an electronic actuator, a SCARA robot, a Flexpicker or an industrial robot could be used for sorting the components and the ejection of such components that are not installed correctly.

Three promising blueprints result from the modeling of the described exemplary production process. The alternatives differ mainly from the form of energy of the actuators (pneumatic or electric), the buffer, the modules for sorting and the sensors (mechanical, optical).

Linked modules exist in addition to these modules, which directly perform a function in the manufacturing process. These linked modules fulfill supportive, comprehensive functions, such as control, safety and communication, which are not mentioned in the process description.

4.3 Evaluation of the concepts with simulation

With simulation models the three different machine concepts mentioned above are tested and compared to identify the best concept at an early stage. The given test scenario is the collision test of single moved axis and benchmarks for the comparison, the operation speed of kinematics and the cycle time of the individual concepts.

For the given task it has to be analyzed if all required modules are already stored in the data-base. New modules have to be assessed and modeled. Therefore the quality and properties of the identified modules are pre-defined by detailed constrictions of the test scenario. The identification- and assessment process can be conducted the better the specification and the goals and important factors are stated. The assessment is done on with an assessment matrix and related elimination criterions to compare and select appropriate modules.

The important properties for the reusable simulation modules were predefined and assessed, but the modules are mainly influenced by the modeling process. For the modeling it is important to focus on the relevant functions and the right degree of details. With this the variables, parameters and interfaces are limited which decreases the effort of the modeling process. The detailed modeling of the vibratory feeder for example causes high effort. But for the machine simulation the functions can be reduced to the output rate to fit the goals of simulation.

The effort of modeling also depends on whether the individual functions or variables are modeled scalable. An example for a scalable variable is the speed of the conveying belt. On the one hand the scalable modeling means greater expenditure of time, but on the other hand it allows a simpler alterability of the module. The reuse of the simulation modules can be realized in various ways as there are direct reuse and recombination, scaling and resetting of variables, and model fitting of the modules. Especially the indirect reuse via the resetting or model fitting leads to a high level of reuse of the modules.

The recombination of the modules enables the reuse of modules without the additional effort. With existing and scalable simulation modules, similar components can be simulated faster. An example might be the simulation module of a SCARA robot which can be adapted to the specification of various robots and robot systems. By the fast scalable and resettable modules, a simulation in the early stage is also possible without detailed engineering-data. The effort of rescaling existing modules is proportional to the degree of adjustment and can vary in individual cases. Depending in the effort, it might be reasonable to re-model the module or even to renew the identification- and assessment phase. The constantly growing simulation module data-base eases the simulation modeling.

4.5 Results of the use case

The three alternative blueprints of the manufacturing system have been modeled based on the modeling of the production process in the configuration tool. These alternatives were simulated in order to obtain a detailed evaluation (Fig. 3). Some existing simulation models could be used for this. But in some cases, new simulation models had to be generated based on the available information of the engineering modules.

Besides the simulated blueprints, there are a lot of other possible combinations of engineering modules. However these are only theoretically possible variants, which were excluded by the pre-selection. This pre-selection is based on a characteristic value, cost or power consumption of the modules.

The machine simulation including collision test was performed for the three concepts. Moreover, the achievable cycle time of processing, and thus the productivity of the manufacturing system could be determined. In an early stage of engineering it was possible to identify the most promising blueprint for the specified requirements deploying the manufacturing system. The use cases with the different concepts show the impact of the new module based approach. The recurring simulation modules could be reused and combined with the simulation model of the different concepts. Individual modules were reused in the different concepts. An example given is the conveyer belt which is used in two concepts. The reuse was foreseen in the modeling process so that this module could be reused indirectly by just resetting the parameters. Other modules like sensors were directly reused. Therefore, it was not necessary to create three different simulation models from the scratch, only a few modules have been modeled particularly.

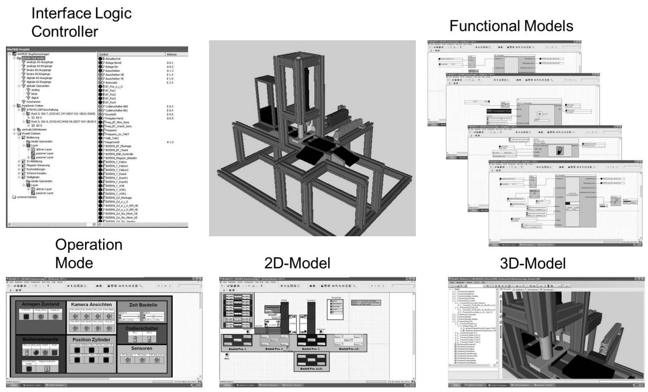

Fig. 3. Machine simulation sample for conceptual evaluation

In the example given concept 1 is not considered for the implementation even is the cycle time and the resulting production rate is very low, as there was a collision during the simulation and the costs are very high. Concept 2 and 3 meet the requirements of the customer with regard to the cost and production rate. Concept 2 was chosen for the implementation, because the cycle time and energy consumption are lower than that in concept 3.

This production process has been implemented after the simulation in the system. The main components of this system are the separation of the components to be assembled, the quality control, the assembly, the sorting device and the storage of components. Other components such as the programmable logic controller are carried out centralized in the system. The modularization resulted in an allocation of the individual components to engineering modules that have been assigned to the functions of the process description.

5. CONCLUSIONS AND OUTLOOK

The presented methodology allows reducing the time for engineering and simulation of new blueprint by reusing mechatronic modules in the conceptual design and basic engineering phase. Therefore, the integration of reusable modules in the engineering process has been demonstrated. The assignment of modules to solution-neutral functions allows the fast modeling of blueprints for a manufacturing process. The most promising blueprints are selected by function to estimate the costs of the blueprints. In addition, our approach allows quickly simulating these blueprints for estimation of cycle time and with avoidance of collisions. Therefore, the modules are adapted for machine simulation. The reuse of modules enables reducing engineering time by avoiding repetitive tasks. Furthermore, the decisions, that are made early in the engineering, are ensured by an evaluation of promising blueprints for manufacturing process. In this paper, the methodology has been illustrated by an example of a special manufacturing system for assembly.

In further research, the evaluation of the modules should be optimized and integrated into the configuration system to obtain accurate values for the cost function in the pre-selection of blueprints. The simulation models could be used in the detailed engineering, start-up and operation of the manufacturing system. Moreover, the approach of the module-based simulation can be extended to other simulation tools, such as system-dynamics or physical simulations.

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