Approaches for the Simulation of Deformable Objects in Manufacturing Systems

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Abstract: The validation of control software using methods of Virtual Commissioning (VC), with its origin in the field of machine tools, gains more and more importance in other application areas like process engineering or material-flow-intensive production systems. Especially because of the increasing complexity of technical systems the validation of the control software quality is a major challenge in production technology. To reduce the efforts of modeling and to increase the value of simulation results, a so-called physically model is integrated in the VC. Currently the physically based Virtual Commissioning is restricted to rigid body simulation objects. In this publication new methods for the simulation of deformable objects are shown and validated in an industrial context. Therefore the hybridization of existing simulation methods from computer science using so called physic engines is introduced as a method that simplifies the description of complex simulation objects by adapting well known simulation models. The new approach is comparable to a mixture of a multi body simulation and a real-time finite element simulation.

Keywords: Physically based Simulation, Virtual Commissioning (VC), Mechatronic, Manufacturing Systems

1. Introduction

Today's production systems contain an increasing part of mechatronic components. They are characterized by a mechanical principle driven by electrical devices and synchronized by complex software systems. This leads to a steady rise of functional integration and an increasing complexity of the technical systems. Therefore new methods are necessary to handle resulting challenges in the development process, especially during the system control design.

To meet these various challenges and to improve the start up of production systems, Virtual Commissioning has been established within the development process. By testing the control software with a digital model of the technical system the development time and the start up time can be reduced. Further advantages are the higher quality of processes and products and the reduced costs for commissioning. But in fact a considerable amount of time is needed to create the simulation models by using existing software systems.

In order to still take advantage of the simulation, a so-called physical model is integrated in VC, containing physical properties such as mass and gravity. These models are evaluated by using physic engines from computer graphics and other fields of computer science. The physical model is calculated in real time and provides the system's behavior for the control software. So far the methods for physically based Virtual Commissioning only refer to rigid body simulation. In many production systems, such as packaging or printing machines, a high amount of deformable objects exists in products and processes. Therefore, the physically based VC has to be enhanced by new methods to simulate deformation.

2. Previous Work

2.1. Virtual Commissioning and Mechatronic Simulation

Simulation has been established within the production technology in order to validate results in an early stage of the development process. Examples are the finite element (FEM) simulation or the multi body simulation in the mechanical development process. Because of the increasing importance of software in mechatronic products, new methods are necessary to handle the growing complexity (Kühn 2006). Therefore, simulation is increasingly used in control engineering. In a so-called Virtual Commissioning (VC) the control system is tested with a digital model of the production system (Röck 2011). As a result, significant savings can be achieved during the development and the commissioning of control systems (Wegener, 2009). Despite the increased quality of control software, technical systems usually require an update every two or three years to meet changing requirements given by short innovation cycles (Albert, 2010). The simulation models of VC can be reused during the product life cycle to optimize the technical system or to train new users (Timmer and Lauscher, 2010). So it is possible to validate changes of the technical system without any intervention in the current operating process. According to that the endurance of production systems can be reduced.

Because of the rising importance of software within the production technology, the approaches of Virtual Commissioning are increasingly extended to the entire development process. The resulting mechatronic simulation can be classified as a method to validate interdisciplinary development results using a digital model of the production system continuously (Reinhart and Stich, 2011) (Hensel, 2011). Therefore, it is necessary to extend the control related methods of VC to the entire development process (Kiefer et al., 2006) and to scale the used methods to the required level of detail (Reinhart and Wünsch, 2007). By the use of modular systems the great potential of consisting mechatronic solution elements can be achieved for low-effort model creation (Zäh and Lindworsky, 2010). The interdisciplinary and functional mechatronic description (Wegmann, 2010) provides an ideal basic for the generation of information models and simulation models for different tasks in the development process.

Beside the major advantages of VC, the methods are not jet as established within the production technology as in the application area of machine tools. This is partly caused by the history of the approach, partly by the complexity of the examined systems. The simulation of the material flow, coupling different machines to a production system, requires additional simulation models to ensure the quality of the simulation results (Spitzweg, 2009). This leads to a main disadvantage of VC: Using commercial tools for Virtual Commissioning the simulation behavior often has to be defined manually in a logical script. Due to that, the modeling is very time consuming (Jensen 2007) (Lindworsky, 2011). Especially for material flow intensive systems it is very costly to build up a simulation model. Moreover the manual modeling process is an additional source for errors in the development process.

2.2. Physically Based Simulation in Virtual Commissioning

To resolve existing problems in VC, the so-called physically based Virtual Commissioning was introduced (Reinhart und Lacour, 2009) (Lacour, 2011). Through this approach the physical behavior of the simulation doesn't have to be defined explicitly in a logical script. Beside the geometrical data the physical model contains additional information such as mass, inertia or friction. These physical parameters and the boundary condition of the technical system are used for the calculation of the physical behavior of the simulation object in real time. Therefore, a physic engine is integrated in the simulation environment. This physic engine provides effective calculation methods for collision detection (van Bergen, 2004) (Ericson, 2005) and collision respond (Millington, 2007), representing the physical behavior (Eberly and Shoemake, 2004) (Erleben, 2005).

An important basis for physically based VC is the method for creating physical simulation models as part of an integrated development and construction process (Zäh et al., 2008), (Reinhart and Lacour, 2010). In this approach existing data from the computer aided design tool chain are used for the generation of simulation models. In addition an actual restriction of the physical model to few simulation objects has been resolved by new simulation methods (Reinhart and Lacour, 2010). Through the derivation of the material flow behavior from the 3D geometry, the programming effort in VC can be minimized (Wünsch, 2010). The approach of physically based simulation of mechatronic systems reduces the modeling process to a parameterization of the physical properties and the kinematics in the simulation models.

The methods of physically based Virtual Commissioning were already evaluated in an industrial context (Reinhart et al., 2011) (Strahilov et. al., 2012). Therefore, simulation models were used to optimize a grouping station from the packaging industry. In many application scenarios the physical model is part of a hardware-in-the-loop simulation. The simulation models are connected to the real control system and other development environments by a standardized data interface. Other input-output devices and human-machine interfaces which are not represented in the simulation can easily be integrated by using standard communication techniques from control engineering.

The major benefits of physically based Virtual Commissioning are the less effort necessary to build up a simulation model, the increased quality of the simulation results and the possibility to simulate large models in real time. The implementation of the new approach in an industrial context validated these existing benefits. By using a physical model it is possible to simulate large production scenarios with over 1000 simulation objects such as material flow and kinematics in real time as shown in Figure 1.

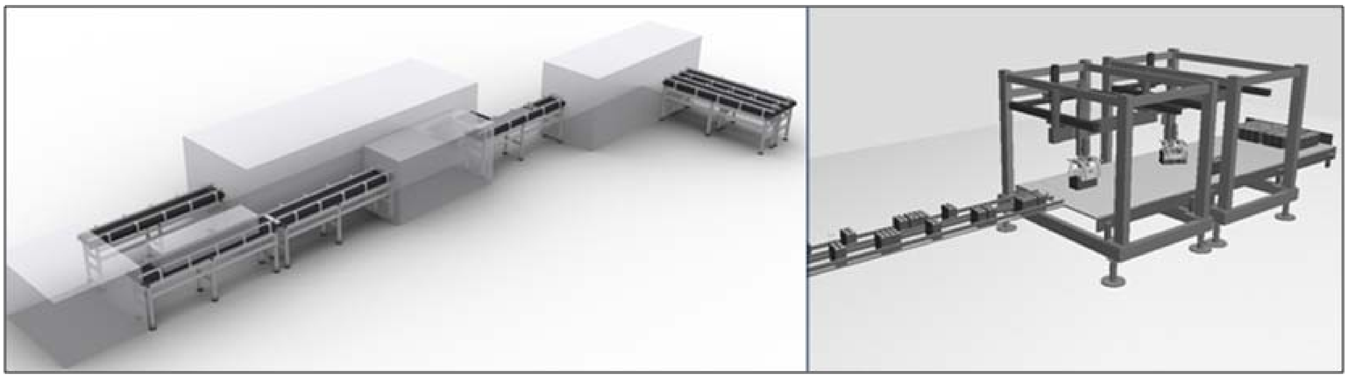

Figure 1. Physically based Virtual Commissioning of large production plants (Reinhart and Lacour, 2011) and detail simulation of kinematic systems (Reinhart et al., 2011)

2.3. Simulation of Deformable Objects

The approach of physically based Virtual Commissioning is currently limited to dimensionally stable objects and less deformable process goods. In many production systems, like packaging or printing machines, a high amount of deformable objects is contained in the products and the processes. Using current methods, the simulation of deformable objects is restricted by the computing power and is limited in case of the validation of complex production systems.

Several research activities in the area of computer graphics and computer science are currently focusing on new approaches for efficient simulation of deformable objects (Georgii et al., 2010), (Servin et al., 2010). However, these innovative approaches are not available in physics engines yet like Bullet or PhysX® and are not yet useable for the physically based Virtual Commissioning of production systems. Furthermore these new methods are restricted to a small amount of simulation objects and unqualified for the simulation of material flow intensive systems such as packaging machines. Another major disadvantage of approaches from computer graphics is the lower quality of simulation results. The main application areas of physic engines are computer games or animations in the movie industry. Thus the requirement is the real time calculation of the collision detection and collision respond. To meet these time constraints, the physical laws are abstracted to a minimum of physical accuracy.

Beside the approaches of computer science very accurate calculation methods for mechanical problems are developed within the engineering disciplines. One of the most promising approaches is the real-time computation of FEM simulations (Röck and Pritschow, 2007). Unfortunately, these approaches are currently limited to only one or a few simulation objects. Additionally the FEM simulation provides only the calculation of the mechanical behavior, such as deformation. Significant for the validation of production systems, however, are especially the interaction of the simulation objects and the resulting change in the system conditions.

For the industrial application of physically based Virtual Commissioning of material flow intensive systems there are various closed software solutions available, such as the Experior (iSILOG GmbH), Demo3D (SimPlan AG) or industrial physics (machineering GmbH). The physically based simulation used by these systems is only possible for a few, mostly primitive, geometries and rigid bodies. In addition to these systems, there are specialized tools for the simulation of deformable behavior available. Examples for these tools are IDO:Flexible (IC:IDO) or IPS Cable Simulation (Fraunhofer ITWM). Due to the restricted usability, for example for wire and hose simulation in automotive application or virtual assembly planning of robot based systems, the specialized solutions are not yet usable in other application scenarios such as from the packaging industry.

3. Requirements

To identify relevant requirements for the simulation of deformable objects, various application scenarios have been analyzed. The amount of deformable components in consumer products and industrial goods is growing steadily. Not only products but also the production processes contain more and more deformable objects such as flexible transport systems, for example rubber lined power supply hoses in robotic applications. Since not all application scenarios can be covered, the analysis was restricted to the consideration of examples in the automotive and packaging industries. Both application areas are representative for complex production systems.

Resulting from the analysis of the application scenarios, the main requirements were identified and classified taking an account of existing requirements for Virtual Commissioning. The most important requirements are the possibility of real time simulation, simulation of friction, online collision detection between different shapes and detection of self contact. Moreover, the accuracy of the simulation and the possibility to simulate elastic and plastic deformation are additional requirements.

4. Physically Based Simulation of Deformable Objects

4.1 Simulation of Deformable Objects using Commercial Physic Engines

Current physic engines provide two possibilities to simulate deformable behavior called cloth simulation and soft body simulation. The given approaches are mostly based on mass-spring systems. In recent decades new calculation methods, like position based dynamic, were integrated in the physic engines to improve the accuracy of the physical model.

Cloth simulation is mainly used for the simulation of two-dimensional geometric objects like textiles or sheets. The physic engines offer a variety of parameters to influence the behavior of the objects. Examples are the thickness, the bending stiffness or the stretching stiffness. Beside these parameters the modeling process and the containing settings like meshing have a big influence on the simulation results.

The second approach is used for three-dimensional deformable objects, so-called soft bodies. The geometry of a soft body is described by a tetrahedral network. As in the case of cloth simulation, many parameters can be defined by the user, such as stretching stiffness, volume stiffness or damping coefficients. Additionally soft body flags, which control the way a soft body will behave, are given.

In different examples the approaches of cloth and soft body simulation were evaluated in cooperation with the Institute for Machine Tools and Industrial Management (*iwb*). The aim was firstly the general validation of this methods for the usage in Virtual Commissioning, secondly the classification of the simulation parameters. Currently, the accuracy of these simulation methods is too low to use them for VC. Especially very stiff objects with small deformation can't be simulated, because of the mass-spring-approach. But the accuracy is high enough to validate results from concept design.

In fact, the mapping of real physical parameters and simulation parameters can not be identified clearly. Therefore, the optimal simulation parameters have to be determined for every single simulation scenario. Because of the various simulation parameters, this process is very time consuming and lowers the economic feasibility of physically based Virtual Commissioning. In a parameter studies (application scenario see chapter 5) regulation guidelines and target intervals were identified, that can be used to adjust the simulation parameters to get the best simulation results. Table 1 shows the key parameters for soft body simulation using NVIDIA® PhysX®.

Table 1. Key parameters and target values of NVIDIA® PhysX® soft body simulation

	collision coefficient	volume stiffness	longitudinal stiffness	Damping Coefficient	Particle Radius	nTET
Value	$Cc = 10 \times \frac{MassSoftBody}{MassCollisionBody}$	0,7 - 1	0,9 - 1	0,7 - 0,8	0,066	10-20

4.2. Discretization and Mono-Hybrid Simulation for Deformable Objects

To still take advantage of the efficient calculation methods of physic engines and to improve the simulation results, a so-called discretization of deformable objects is introduced. The discretization is already used for the simulation of one-dimensional objects like cables or hoses (Servin et al., 2010). This approach is now extended to multidimensional simulation objects.

The first step of the new approach is the fragmentation of the volumetric data in specific shapes, as shown in Figure 2. These partial objects are, in a second step, connected by defined elements. Physic engines provide different types of connections called joints. These joints, also used in multi body simulation, define the way two bodies are linked in the simulation. Beside the degrees of freedom only the parameterization of spring and damping values for joints is necessary. The deformation behavior then depends on the used fragmentation and the parameters of the links. Compared with the parameterization of cloth or soft body objects, the effort of parameter identification and optimization can be reduced. Figure 3a shows different examples of a mono-hybrid simulation using existing physic engines. The hybridization results as a combined simulation of rigid bodies connected via links. Using this method, the given requirements can be covered, except plastic deformation. Another advantage is the definition of partial physical parameters and heterogeneous simulation behavior.

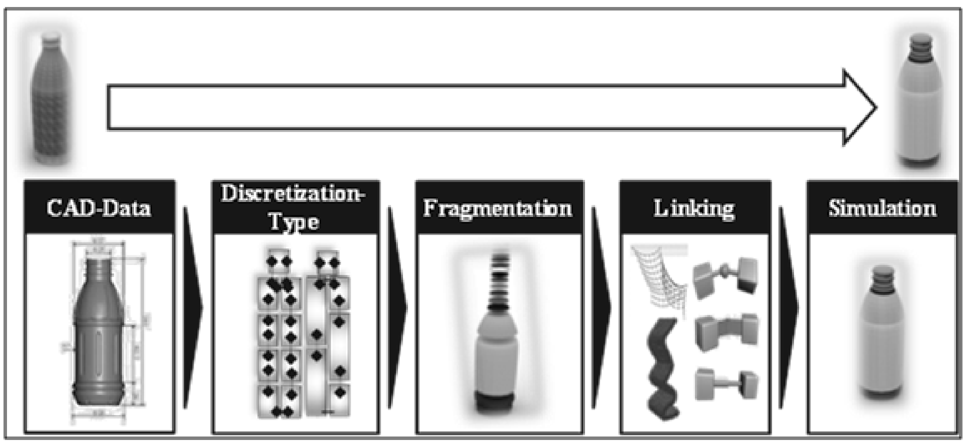

Figure 2. Modeling process for hybrid simulation of deformable objects

4.3. Multi-Hybrid Simulation for Deformable Objects

The mono-hybrid simulation method allows the real time simulation of deformable objects. But with this approach, comparable to a reduced real time multi body simulation, the simulated objects have a heterogeneous surface. In some scenarios, like simulation of kinematics or calculation of friction, this can be a major problem. For that reason, the mono-hybrid simulation is extended by cloth and soft body objects, which represent the surface of the objects, as shown in Figure 3b.

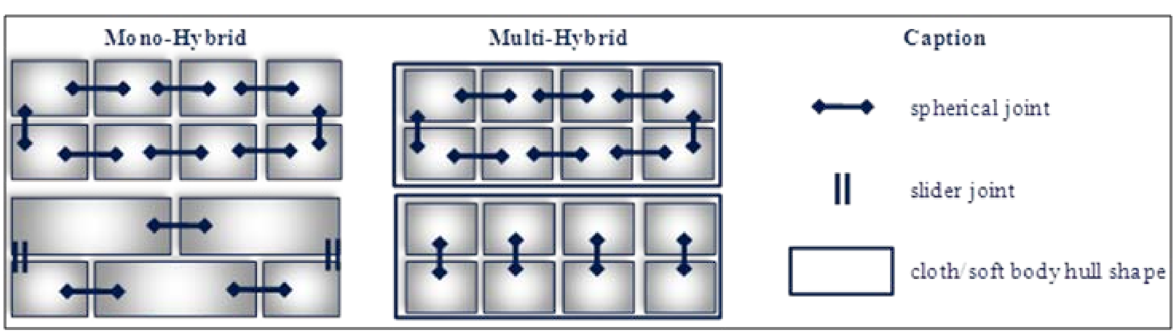

Figure 3. Simplified examples for mono-hybrid (a) and multi-hybrid (b) simulation using different discretization

5. Validation and Results

The approach of the discretization of deformable objects has been validated in an industrial context. The simulated examples were an application from the packaging industry and a handling process for composites in the automotive industry. Therefore, a physically based model was implemented. The simulation models are shown in Figure 4.

The packaging good was simulated by an assembly of several cloth elements combined with a mono-hybrid shell of rigid body plates, connected by spherical joints. For the packaged good the multi-hybrid approach was chosen, containing partial rigid body fragments and a cloth cover. The simulation of the composites contains a net of particles connected with spherical joints. During the validation, the discretization of the objects and the simulation parameters were varied to indentify the optimal parameters. In conclusion, all requirements given in paragraph 3 were covered, except the plastic deformation. Further research is still necessary to map the influence of the discretization and the simulation parameters to the real system behavior.

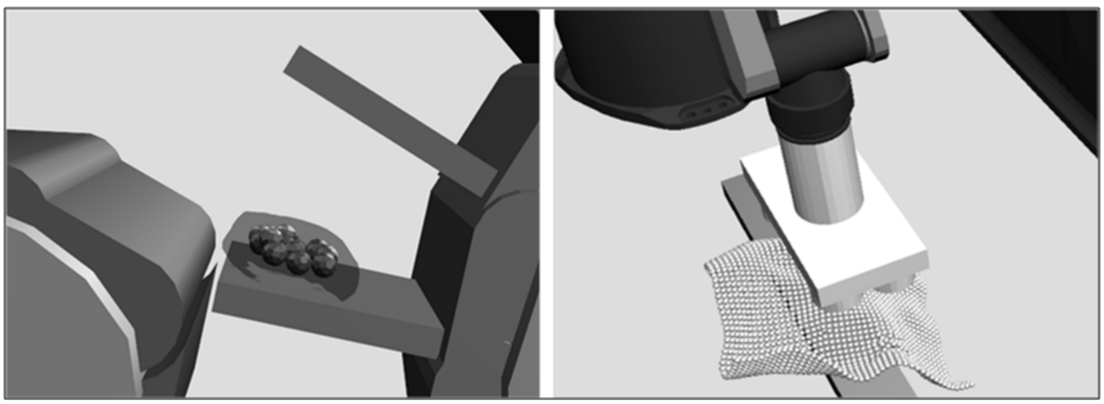

Figure 4. Simulation models from packaging industry (Somic, 2011) and automotive industry

6. Conclusion and Future Work

The presented approach of the discretization and mono-/multi-hybrid simulation using existing physic engines is a promising solution to simulate deformable objects in Virtual Commissioning. Based on an introduction to VC and related fields, the resulting requirements and the new methods were presented. The validation showed the great potential of the mono- and multi-hybrid simulation.

Currently joints from physic engines are used for the links between the discretized simulation objects. Nevertheless the optimization of the simulation parameters of these joints is still an expense factor of the presented approach. In order to solve that problem, so-called hooke's joints are developed at the *iwb*, combining the efficient calculation methods of physic engines with real physical behaviors. Additionally distributed computing of physical models is a focus of current research projects. Goal of these projects is to reduce the need of computing power for real time simulation in VC. In summary, the new approaches contribute to expand the application area and to increase the economic efficiency of Virtual Commissioning.

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