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DEVELOPMENT OF THE PHYSICS-BASED ASSEMBLY SYSTEM MODEL FOR THE MECHATRONIC VALIDATION OF AUTOMATED ASSEMBLY SYSTEMS

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ABSTRACT

As the complexity of automated assembly systems increases, so does the number of errors which arise during their development. The challenge is to avoid these errors already in an early stage, thus reducing development time and costs. This cannot be done without using digital simulation methods. In order to be able to apply these methods in an effective way, the digital simulation models need to abstract reality as much as possible. One key topic is the simulation of the physical behaviour of the components in assembly system. In order to be able to simulate this behavior, additional information within the simulation model is required. This paper proposes a methodology to build such models. The method focuses on identifying what kind of information is necessary for each type of component in order to achieve the desired realism. In doing so an automated and therefore less laborious modeling is possible.

1 INTRODUCTION

Developing complex automated production systems without the use of computer-aided simulations is now unthinkable. In order to enhance the validity of such simulations, simulation models need to abstract reality as much as possible, thus allowing to make right decision about the systems they represent at a reasonable modeling effort. The enhancement of these simulation models through physical characteristics is one of the possibilities to reach a more realistic approach. Various approaches show how physical characteristics can be displayed for analysing physical behaviour of plant components. Amongst them the following can be mentioned: kinematic dependencies, dynamics, as well as the plant components' forces. The simultaneous simulation of such physical characteristics cannot be realised in real-time with the common available methods (Roylance 2001). One example of this is the use of the finite element method for the simulation of deformation of diverse components (Emmrich 2009). With the use of physical behavior simulation methods from the computer game industry, a real-time assembly system simulation will be possible . First applications show for example, that material flow in automated plants can be displayed in real-time (Boeing and Bräunl 2010). Using physics-based simulations for the validation of automated assembly systems is a thinkable and reasonable enhancement for the digital validation methods used so far.

In order to address the aforementioned situation, a method for the simulation of the physical behavior of automated assembly systems during digital validation is introduced. A detailed presentation of one of the building blocks of this method, i.e. the creation of physics-based assembly system model, is present-

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ed. Among the most problematic topics concerning the model generation are the following: keeping the modeling effort as low as possible and making one single model usable for several types of simulations. The latter is mainly due to the fact that different software tools address different types of simulations, and that the model information requirements vary from one use-case to the other. Hence, this paper proposes a tool-independent method, with which the physics-based simulation model of an automated assembly station can be generated.

2 MOTIVATION

For a complex vehicle to be produced in a high quantity and in a cost effective way, highly complex automated assembly systems are needed. The planning of these complex systems often leads to a high number of errors, which are only detected during commissioning (Zäh and Wünsch, 2005). Due to lack of time these errors are often only eliminated provisionally. Automated assembly systems are designed in such a way that several product variants can be produced in the same plant, so the problem arises that not all product variants are available during the planning of the assembly systems. Furthermore only a couple of product variants are mostly made available to the supplier. As a consequence the supplier is not able to validate the plant with regard to all product variants.

Further typical characteristics of automated assembly systems are desired physical effects. This means that physical effects can be utilised in order to reach certain design requirements of the assembly plant. A typical example for this is the desired friction between a conveyor- band and the conveyed component. The physical effects which occur from one product component to the other are also of great importance for the correct physical behaviour of the plant components. Another example for the application of physical effects is the limitation of the travelling distance of a pneumatic cylinder with the help of mechanical stops.

Furthermore cables and tubes used in assembly systems constitute an enormous source of errors. With the help of today's planning and validation methods they can be detected in simulation models only in a time-consuming way. By using physics-based simulations not only the effort for the model building but also the validity of the simulation can be improved. Due to the real-time capability of these physics-based simulations, the amount of time needed for the actual calculation of the results can be significantly reduced. It would also be thinkable to validate new product variants on the assembly system itself with the help of physics-based simulations before this happens in the real plant. That way plant changes could also be validated on all available product variants without wasting time or further investment costs.

3 TERMINOLOGY

In order to ensure full understanding of the presented concept this section aims to define the most important terms.

Physical behaviour describes, from a physical point of view, the behaviour of a component in an assembly system towards other components and also their mechanical behaviour as a result of external forces. According to VDI-2221 the term effect is defined as a predictable event which is determined by the laws of nature and is described by physical, chemical or biological dependencies.

This paper mainly focuses on physical effects. There is an enormous amount of various physical effects. In this paper only those physical effects that have a direct influence on the motion and deformation of a body will be considered. Mechanics is the area of physics which deals with these effects (Dobrinskiet al. 2006). Mechanics itself can be classified into kinematics, dynamics and strength of materials. Kinematics deals with the motions of points and bodies that are in certain dependencies to each other. Thereby resulting motions are dealt with, and not the causes. Dynamics, on the other hand, deals with the resulting motions as well as with their causes (for example all external forces) (Mahnken 2010). Strength of materials deals with the effect of external forces on the geometric form of a body (Lugner, Mack, and Plöchl 2010). In this article the components are divided into two main groups according to their strength behaviour, i.e. rigid and flexible components. Rigid components are all those components that do not or only insignificantly change their original form upon experiencing external forces. Flexible components, on the other side, are all those which undergo an important elastic deformation when influenced by minor external forces (Mahnken 2010). In this article the focus is mainly on cables and tubes as flexible components.

Multi-body systems (MBS) describe, based on kinematics, the kinematic behaviour of individual rigid components, which can found themselves in a precisely defined dependency from each other within the system. The simulations based on this are named multi-body simulation. In addition to the pure kinematics view in various cases of application also dynamics and rigidity are considered.

4 STATE OF THE ART

In (Spitzweg, M., 2009), (Bräckelmann and Predki 2006) and (Stetter 1993) various methods are presented that have been developed for a digital validation considering physical behaviour of assembly components. In doing so it is important to know which methods are available that can respectively model and simulate physical behaviour. Furthermore the available digital methods for the validation of plants need to be considered. These two issues will be discussed more precisely below.

4.1 Simulation of Physical Behaviour

4.1.1 Simulation of Physical Behaviour of Rigid Components

In order to represent and simulate the kinematics and dynamics of rigid components, rigid body simulation has been developed. One type of rigid body simulation is presented in (Stetter 1993). Here the physical behaviour of plant components is presented based on momentum equations. Combining this method and the multi-body simulation, a collision detection in real-time is not practicable with today's resources due to the enormous needed processing power (Reinhard and Lacour 2010).

Collision detection on the other side is important in order to determine how the body behaves during and after the collision (Spitzweg 2009, Kaufman et al. 2010). Various approaches showed that such a collision detection is only possible with the help of extensive modelling. The reason for this is the model preparation necessary to define all possible collision conditions. One example is to define the collision conditions between one point and all possible surfaces.

4.1.2 Simulation of the Physical Behaviour of Flexible Components

Several examples show that besides the pure rigid body simulation also a deformation of the components can be simulated (Schaeffer et al. 2009). These deformations are calculated based on the finite element method. The preparation of the therefore needed model is very time-consuming. Furthermore this method for flexible components is not applicable in a reasonable way. The reason for this is the complex meshing and the enormous computing time. For these purposes other methods which can be used for the simulation of flexible components have been developed. An extensive explanation is given in (Wienss 2008).

4.1.3 Physics Engines

Physics engines are based on new methods and algorithms which help to reduce the computing time (Eberly 2004)(Boeing and Bräunl 2010). Physics engines are software libraries which simulate physical behaviour based on physical characteristics (for example mass and elasticity modulus) .In (Kaufmanet al. 2010) various methods that are used for the collision handling in physics engines are described. Here the real-time capability of these simulations has more advantages than the conventional approaches. One only needs to be aware of the fact that the complexity of the models cannot be very high. This means that the number of components which are available in the simulation model is limited (Boeing and Bräunl 2010).

4.2 Digital Validation of Automated Assembly Systems

Planning of automated assembly systems affects three areas which can be differentiated according to their function: mechanic construction, electrical engineering and control engineering. For the scope of the present paper only the mechanical design and the control engineering are considered.

4.2.1 Support for Mechanical Design

(Spitzweg, M., 2009) presents a concept which has been designed for developing assembly systems with the help of physical models. The focus of this paper is on assembly systems. The difficulty is that an enormous effort needs to be invested in order to correctly represent the complex conveyor systems in the simulation. Moreover the conformity with reality of these simulations is limited. Furthermore mainly rigid components are considered: Both, the kinematics and dynamics of the components and also the friction between them is simulated with the help of physics engines.

4.2.2 Virtual Commissioning

(Kiefer et al. 2009) presents virtual commissioning as a method for validating control engineering even before the real commissioning. In order to be able to accomplish the virtual commissioning, a model of the plant is needed. This model is called mechatronic plant model. This model is divided into the so-called extended 3D-geometry model and the behaviour model. For the visualization of the resulting motions the extended 3D-geometry model is needed. It is the task of the behaviour model to simulate the behaviour of the plant components upon certain signals. An implementation of the aforementioned approach including a physics-based simulation in virtual commissioning is presented in (Spitzweg 2009).

4.2.3 Validation of Flexible Components in Assembly Systems

Up to now flexible components are neither considered during the mechanical validation nor during the virtual commissioning. The reason for this is that these automated assembly systems are custom made. Usually these plants are one of a kind. In addition, the current modelling effort of cables and tubes is enormous, so that digital validation would not be profitable.

5 SIMULATION OF PHYSICS-BASED BEHAVIOUR IN DIGITAL VALIDATION OF AUTOMATED ASSEMBLY PLANTS

5.1 Requirements on the Overall Concept

The overall concept needs to meet the following four requirements:

- The simulation model needs to be suitable for various interdisciplinary tasks (for example simulation of the assembly system sequence and virtual commissioning).
- The simulation effort must not exceed the additional benefit achieved by the simulation results.
- The real-time capability of the simulation needs to be granted both for the assembly system sequence and also for the virtual commissioning (connection with control systems).
- The results from the simulation need to be completely transferable into reality.

5.2 Overall Concept

The accomplishment of the overall concept can be split up in three steps. In step 1 the physics-based plant model is built. In this phase also a physics-based product model is created in order to be able to display the physical behaviour of the product components. In order to be able to build the physics-based plant model the 3D-geometry model of the plant and the product variants are needed. Moreover the material characteristics of the plant components are of importance. The next step is the mechanical validation, based on the workflow description and the physics-based plant model. In a last step the validated physics-based plant model is also used for the validation of the control software. The real commissioning which then follows is not described more extensively in this concept. A main component of the overall concept is the preparation of the physics-based plant model (step 1, figure 2). For this, further steps are necessary. These will be covered more precisely in the following chapter.

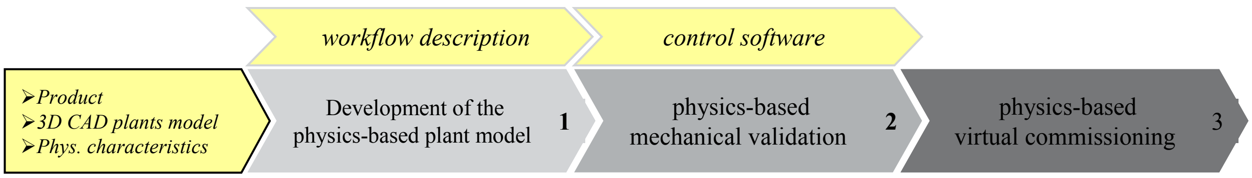

Figure 2: Overall concept

6 DEVELOPMENT OF THE PHYSICS-BASED ASSEMBLY SYSTEM MODEL FOR THE MECHATRONIC VALIDATION OF AUTOMATED ASSEMBLY SYSTEMS

6.1 Concept

The preparation of the physics-based plant model can be split up in four steps. When doing so, the order in which the individual steps are performed is relevant. To begin with, the 3D-geometry model is adopted as the starting point. This model represents the 3D-geometry as well as the positioning and orientation of the components within the plant. All components which are available within the plant are displayed individually in this model. In the next section the four steps are explained.

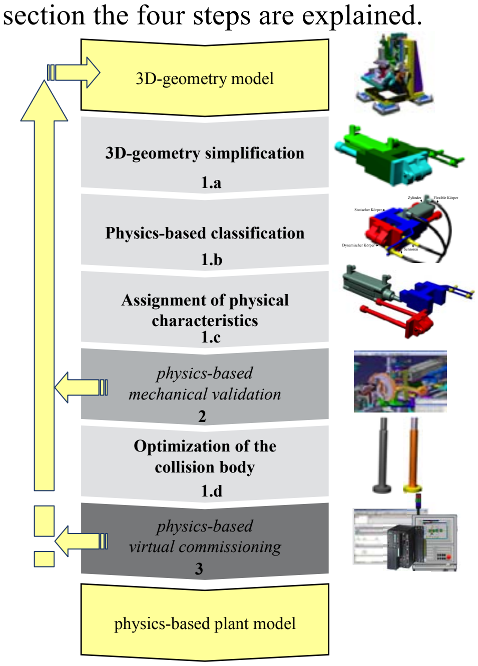

Figure 3: Development of the physics-based plant model

- **3D-geometry simplification (1.a)**

In this step the method for the simplification of the 3D-geometry model, presented in (Strahilov, A. 2012), is used. To begin with, all standard parts and purchased parts are exchanged with replacement models. Then the features of the remaining components are removed, e.g. drill holes and empty spaces. In a next step all individual components which accomplish exactly the same motion are merged into one component. For the mechatronic validation of the plant the physical behaviour of fasteners, such as bolts, are not of interest. This is why these fasteners are merged into the components. However it needs to be considered that when merging, the components' masses need to be added up. These will then be tessellated in order to reduce the triangle quantity. The admitted discrepancy between the real geometry and the tessellated representation depends on the required exactitude when accomplishing the collision detection and the respective collision handling (Strahilov, A. 2012). This is important, as otherwise the admitted discrepancy would alter the collision bodies and, as a consequence, also the simulation result.

- **Physics-based classification (1.b)**

In this step mainly three types of bodies are distinguished. Those bodies which cannot move within the plant can or should be classified as static bodies. Such bodies are for example the basic frame of the plant. Furthermore all bodies which can move freely within the plant are called dynamic bodies. Distinction needs to be made between bodies which can move in a limited way and those which can move freely. Bodies which move in a limited way have a kinematic dependency from other bodies, which in turn can be either static or dynamic. All the remaining dynamic bodies can be classified as free moving-dynamic bodies. Finally the flexible components need to be defined, these are mainly cables and tubes in the plant.

- **Assignment of physical characteristics (1.c)**

By classifying bodies into static, dynamic or flexible, the body's material characteristics required in the model are determined. A static body, for example, does not need any mass for the simulation, as it is defined as non-flexible and therefore cannot experience any alteration of the position. For dynamic bodies, however, mass is an important factor, to be able to calculate the physical behaviour in an accurate way. Mass can be determined with the help of material density and the volume which depends on the 3D-geometry. Furthermore static and dynamic bodies are influenced by the friction coefficient. These bodies are handled the same way as rigid components, which means that in contrast to flexible bodies the elastic modulus does not play a role. Besides the material's Young's modulus elastic coefficient also the flexural rigidity, as well as the ultimate and torsion strength need to be known (Wienss, C., 2008). In this way all information which is needed for the physics-based simulation is available.

- **Optimization of the collision body (1.d)**

In this phase only the dynamic and static bodies are handled. Generally they are available as concave geometry models. This means that the required computing power increases considerably (Spitzweg, M., 2009). In order to optimize this, the method presented in (Reinhard, G. and Lacour, F., 2010) is used, where concave bodies are broken down into several convex ones. By accomplishing this, the needed computing time is reduced. As a consequence the calculation time is decreased, thus the real-time ability of the simulation model is granted. When accomplishing this break down into convex components the geometry models are modified, which means that the deviations for a mechanical validation become inadmissibly huge. For this reason concave bodies will only then be broken down into several convex ones within the physics-based plant model if the mechanic validation has been successfully completed.

6.2 Role-based development of assembly systems

Usually assembly systems contain a certain amount of components which are used repeatedly. One example of this are pneumatic cylinders. For this reason, it is reasonable to store them in a library and to use them as needed during the development of the assembly systems. Furthermore the assignment of roles to the components within the 3D-geometry model is advisable. In this way the various characteristics which are decisive for a certain simulation can be obtained through these roles. As an example, in defining the role of a "cylinder" for the physics-based plant models, the kinematics can be defined. In addition it can be determined that the cylinder needs to have at least two end positions and as a consequence has two sensors. This information can also be used for control engineering, for example for definition of signals. With the help of these roles the development of the physics-based plant model can be simplified or significantly automated.

7 IMPLEMENTATION

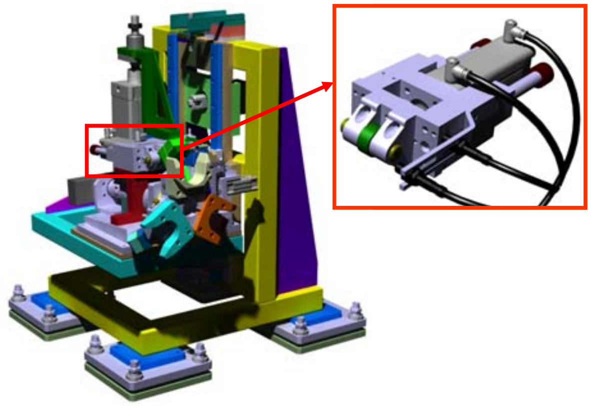

Figure 4: Detail of a 3D CAD plant model of an automated assembly system

In this chapter the proposed concept for the building of the physics-based plant model is demonstrated with the help of an example. This example is an extract of an automated assembly system from the automotive industry. For the accomplishment of the individual steps only one function group of this plant is used (figure 4).

- **3D-geometry simplification (1.a)**

For the accomplishment of this step it is assumed that replacement geometry models of normed and standard components are already available. These will then be exchanged in the plant model. In a next step all holes, empty spaces etc. are eliminated. For this example this is acceptable, as these features do not have a significant impact on the 3D-geometry. In a next step the individual components are merged as components which accomplish exactly the same movement. Cables and tubes are preserved as separate components. In a last step triangle quantity is reduced. For this example a deviation of 2mm is admitted. The results are depicted in figure 5.

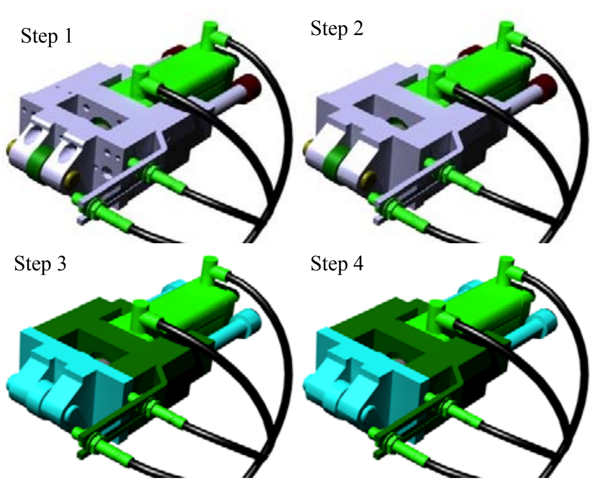

Figure 5: Results from the simplification

Table 1: Count results from the simplification

	Original	Simplification	%
Triangles	14884	4545	69,5

Data volume [MB]	6,12	1,66	73
Parts	23	6	74
Time [min]	-	20	-

- **Physics-based classification (1.b)**

In this phase it is important to know the function of the individual body. The example shown in figure 6 is an assembly group which consists of a cylinder (grey), two sensors (yellow), one dynamic (red) and one static (blue) body. The cylinder is connected through two tubes and the sensors are connected each with one cable (flexible bodies are represented in black). In order to make sure that the cylinder is preserved it is not merged with other bodies. In this way the cylinder remains a separate component, which is important in order to guarantee a simple replacement of the cylinder within the physics-based plant model. Based on the functions of the individual bodies also the kinematic relationships between the static and dynamic bodies are defined. It must be kept in mind that the kinematics in the cylinder had already been defined in the replacement geometry model. Figure 7 illustrates the operating mode of the cylinder, which enables the determination of the kinematics.

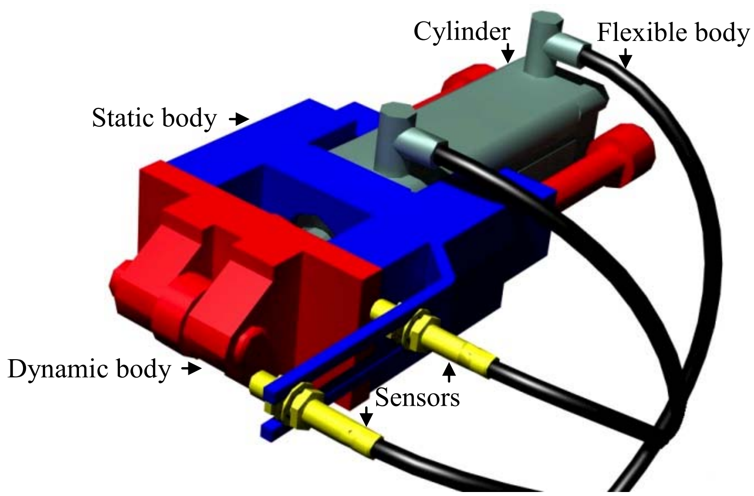

Figure 6: Physics-based classification of the bodies

- **Assignment of physical characteristics (1.c)**

Based on body type, the material characteristics to be present in the model are defined. In figure 7 the material characteristics which need to be assigned are summarized. It needs to be considered that the static body has also been assigned a mass. The reason for this is that this body in the function group is static, however it is still possible for this body to move as part of another function group within the entire assembly system and, as a consequence, its mass is relevant for the simulation.

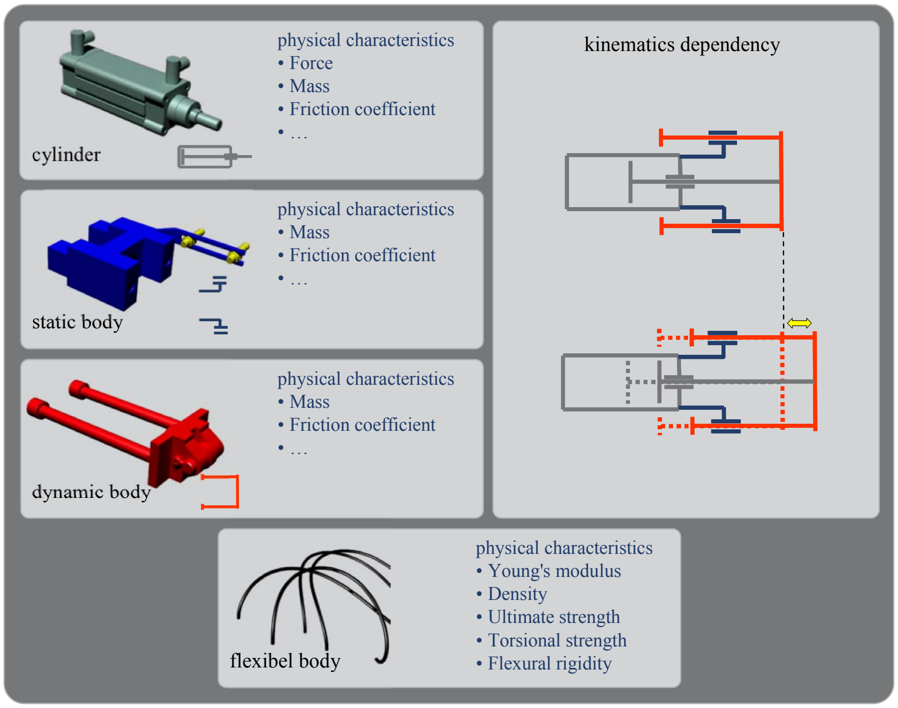

Figure 7: Allocation of physical characteristics

- **Optimization of the collision bodies (1.d)**

In this phase it is important to decompose the static dynamic bodies, which are concave geometry models, into individual convex bodies. For instance, the piston which is defined as dynamic, can be decomposed into three simple cylinders (illustrated in different colours). In doing so they still remain as an entire body. The result is shown in figure 8. The consequences of such an optimization on the exactitude of the body can also be appreciated.

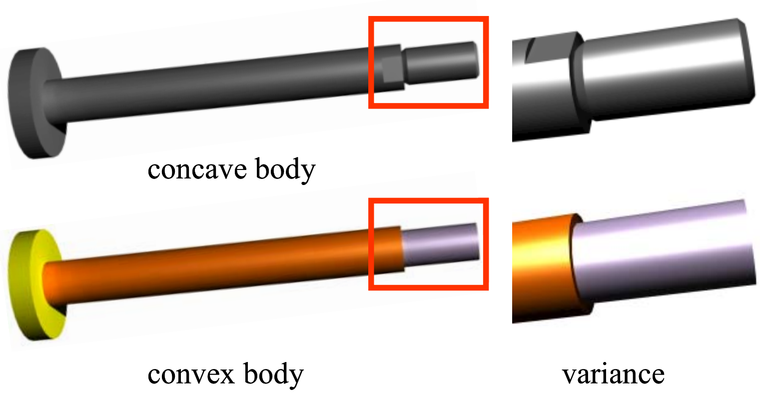

Figure 8: Physics-based classification of the bodies

7.1 Role-based development of assembly systems

The functions and also the physical behaviour can be adopted directly from the roles. With the help of the example it becomes clear how the roles can be interpreted. In the function group there are one "cylinder", one "static" body, one "dynamic" body and two "sensors" available. These roles are determined by the

3D-plant model provided that they are defined there (the structuring of the assembly hereby plays a considerable role). Furthermore it can be determined that the actuator is a "cylinder". From the role "cylinder" it can also be inferred that two "sensors" must be defined, these are connected in a mechanical way with the "static" body. From the role is also possible to realize that the "cylinder" is connected to the "dynamic" body through the piston in a mechanical way. It is therefore necessary to consider that the "dynamic" body itself is in kinematic dependencies with the "static" body. Figure 9 depicts these dependencies. All of these correlations can be realized on the base of roles.

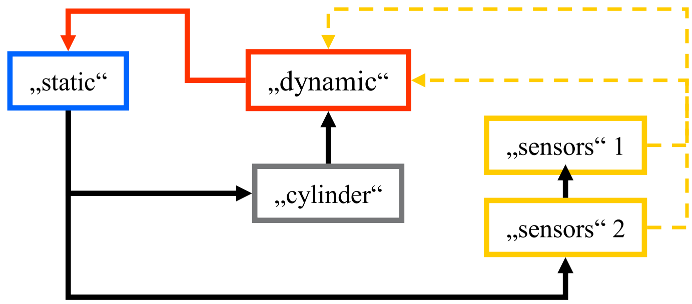

Figure 9: Physics-based classification of the bodies

8 SUMMARY

Through the use of digital methods for the validation of complex mechatronical systems, like automated assembly systems, industrial companies can expect to reduce development times and increase the quality of their products. Due to the complexity of automated assembly systems and the underlying physical interactions among their components, these physical effects must be addressed and taken into account during digital validation. The concept introduced in this paper proposes a method for the digital validation of automated assembly systems, which is able to address the mechanical validation as well as the virtual commissioning, while taking the physical behaviour of its components into account. In order to carry out this validation, a model of the system is required. Usually the generation of this model takes much more time than the validation itself. Based on this, a role-based method is introduced in which a physics-based model of the system is generated.

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