BRIDGING THE GAP BETWEEN OVERALL SYSTEM SIMULATION AND FINITE ELEMENT ANALYSIS – AN EROBOTICS APPROACH

Dorit Kaufmann [(1)], Malte Rast [(1)], Jürgen Roßmann [(1)]

[(1)] Institute for Man-Machine Interaction (MMI), RWTH Aachen University, Ahornstr. 55, 52074 Aachen, Germany, Email: {kaufmann; rast; rossmann}@mmi.rwth-aachen.de

ABSTRACT

Space robotics systems consist of a huge variety of different components working together and coming from different domains. Thus, it is crucial to test all the components and their interplay to guarantee a reliable functionality in space prior to the real mission. There exist powerful simulation tools to model a certain aspect of a system, like structural deformation, which can be analysed with Finite Element Analysis (FEA). This method is used as a stand-alone tool to e.g. optimize lightweight construction. Nevertheless, errors in functionality often occur due to the interaction of several components with each other or with the environment. This requires an Overall System Simulation for the early validation of the system in a Virtual Testbed. To consider both the details and the overall picture of a real-life scenario in the same framework, an interaction between FEA and a Virtual Testbed was implemented in this work.

1. INTRODUCTION

A sophisticated and cheap way to analyse a real-life scenario prior to production are simulations, which are used to spot defects and optimize the whole system. This is especially needed in space robotics, as the components combine different domains, like electronics, mechanics, materials science, data processing and many more. Additionally, there often is a lack of an adequate test environment on earth. As soon as new components for space missions are developed, the problem arises, that they have to perform their task reliably while simultaneously fitting in the overall structure. Even defining the requirements for a special component cannot be done easily here, as the individual components are highly dependent on each other. Thus, planning a space mission often faces a vicious circle. One common example concerns materials science and robotics: a material can only be reasonably developed, if the acting loads are well defined. A robot causes them while fulfilling his task. On the other hand, the robot itself will be affected by structural deformation of the material – this problem cannot be solved on neither side. Simulating all different components of a robot, satellite etc. can be done with many simulation tools; nevertheless, most of them neglect the interactions between the individual components, which are often additionally associated with different research topics. This is overcome by a Virtual Testbed, a concept from the emerging field of eRobotics, which not only puts all components in the same framework, but also considers their interaction with the environment and provides a 3D-visualization for the user. Virtual Testbeds can serve as a tool to simulate whole space missions. In best case the simulation algorithms are universally applicable and real-time capable. This is combined with a graphical user interface, which is intuitive to use and does not require any programming skills. For most cases, this framework is sufficient to provide physically correct results. However, when it comes to more sophisticated concepts, further aspects need to be considered. This is true for structural deformation, which for example become relevant in lightweight systems working under the harsh conditions in space. Structural simulations provide the deformation of components due to an environmental load, as heat, force, momentum etc. Furthermore, deformations due to implicit acting forces like in joints or bearings can be calculated. This information is important for durability tests and is usually done using Finite Element Analyses (FEA). The results are evaluated in a stand-alone analysis and cannot be included in the overall system directly, as the simulation methods use a completely different mathematical and physical model. Furthermore, FEA in general are memory- and time-consuming, one analysis of a complex structure can take up to several days of calculation time.

This work closes the gap and completes the existing Virtual Testbed with results from structural simulations. Different approaches were implemented to allow the integration of different application scenarios. Examples from space robotics show the benefit of such a completed Virtual Testbed, when e.g. the described vicious circle between material sciences and robotics in space missions is overcome. Results from materials science are included in the overall system or vice versa, the Virtual Testbed delivers the loads needed for efficient dimensioning of structural parts to meet the requirements for a stable component.

2. RELATED WORK

Both FEA and Overall System Simulations are rather sophisticated today and there exist powerful tools for each method. Thus, the next level of complexity is combining FEA with other software [1]. This faces some severe problems, as FEA naturally deal with deformable

components. In consequence, FEA have a much longer calculation time and different claims for the underlying algorithms compared to models consisting of rigid bodies.
Until today, no generally acknowledged method exists to enable an interaction between FEA and an Overall System Simulation. Every approach either has a focus on a mathematical description of the problem and is thus rather theoretical or deals with a specialized application and therefore allows no widespread use. The theoretical approaches mostly use a classical co-simulation [2]. Special attention has to be paid to extrapolation and time-handling strategies [3],[4]. This finally results in complex algorithms, which cannot be used for generalized applications. Especially real-time capability is one of the major problems, that has to be resolved in the future [5]. On the other hand, the interaction between FEA and other simulation tools is needed in various domains of engineering. Several groups work in the domains of robotics [6],[7], automotive [8] or even bio-engineering [9]. In most cases, critical situations are detected in the Overall System Simulation and the acting forces are taken as a basis for the following structural simulations. Another widespread method is to use a modal analysis out of FEA to find possible unwanted vibrations as in [10]. Especially in aerospace engineering, structural effects play an unneglectable role [11], why an integration of FEA results is strongly needed. A reliable stability is crucial for each component, at the same time, the smallest possible weight has to be achieved. Thus, fatigue analysis and structural simulations are used to optimize a component. Furthermore, FEA can be helpful when designing a new material for a certain application, as it can be done e.g. with carbon-fibre reinforced polymers.

3. KEY METHODS

The Overall System Simulation uses Rigid Body Dynamics (RBD) to calculate the behaviour of single components. In general, forces/momentums and positions/orientations are assigned to each Rigid Body (RB). Thus, this part is crucial for an interaction with FEA, as certain RB shall be replaced with deformable structures. The functionality and underlying mathematical models of both FEA and RBD have to be analysed before implementing a reasonable form of interaction process.

3.1. RBD

Several simplifications are made to calculate the dynamic behaviour of RB in an efficient manner. To each component its collision hull, centre of mass and inertia tensor is assigned. With theoretical mechanics it is possible to compute the movements of simple models. Taking into account linkages to other RB, the model gets more complex, as movements in certain directions are prohibited. This is known as a constraint acting on the component. It is intuitive to introduce a force that causes this restriction, i.e. a constraint force $\boldsymbol{Z} = \lambda \cdot \nabla f$, where ∇f points in the direction of the force and λ is a Lagrange multiplier. Consequently, the constraint force needs to be added in the Newtonian axiom, what finally results in the Lagrange equation.

$$m\ddot{\boldsymbol{r}} = \boldsymbol{F_{ext}} + \lambda(t) \cdot \nabla f(\boldsymbol{r}, t) \qquad (1)$$

Another important conclusion is that the constraint force only forbids movements in direction ∇f. Therefore, movements or analogously velocities $\dot{\boldsymbol{r}}$ perpendicular to ∇f are allowed. This leads to a so-called holonomic constraint, introducing a constant b.

$$\nabla f \cdot \dot{\boldsymbol{r}} = b \;\; \Leftrightarrow \;\; \nabla f \cdot \dot{\boldsymbol{r}} - b = 0 \qquad (2)$$

Eqs. 1 and 2 are the conceptual ones to solve the mathematical problem of RBD. Nevertheless, in [12] a momentum/velocity-based approach was presented, that is much more performant than the force/acceleration-based approach. This is crucial considering that the equations shall be solved in systems with real-time capability requirements. Thus, a simple integration with time step h is introduced:

$$\ddot{\boldsymbol{r}} = \frac{\dot{\boldsymbol{r}}(t+h) - \dot{\boldsymbol{r}}(t)}{h} \qquad (3)$$

The characteristic equations in a momentum-based form can be combined to finally form a Linear Complementary Problem (LCP), which can be efficiently solved by different standard algorithms [13].

$$\begin{pmatrix} m & -\nabla f(\boldsymbol{r}, t) \\ \nabla f(\boldsymbol{r}, t) & 0 \end{pmatrix} \cdot \begin{pmatrix} \dot{\boldsymbol{r}}(t+h) \\ \lambda(t) \cdot h \end{pmatrix} - \begin{pmatrix} \boldsymbol{F_{ext}} \cdot h + m \cdot \dot{\boldsymbol{r}}(t) \\ b \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad (4)$$

3.2. FEA

FEA is a standard method to describe the structural behaviour of a deformable component. The general procedure is to give an outer influence as an input to the simulation and get the according reaction of the component as an output. Examples are applying external forces or thermal load and getting the resulting deformation or heat distribution of the body. This kind of mathematical problem is represented by differential equations in continuum mechanics. As an analytical solution can be only achieved in the easiest cases, the problem needs to be solved numerically. Therefore, the deformable structure is separated into multiple elements, which are linked to each other by nodes and edges. A basic function to describe the deformation is applied to each element i. Considering the material characteristics $\boldsymbol{k_i}$, it is possible to get the displacement $\boldsymbol{u_i}$ out of the acting forces $\boldsymbol{f}_i$ [14]:

$$\begin{bmatrix} \boldsymbol{k}^1 & & 0 \\ & \ddots & \\ 0 & & \boldsymbol{k}^m \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{u}^1 \\ \vdots \\ \boldsymbol{u}^m \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}^1 \\ \vdots \\ \boldsymbol{f}^m \end{bmatrix} \equiv \boldsymbol{k} \cdot \boldsymbol{u} = \boldsymbol{f} \quad (5)$$

Solving this equation is rather complex, as two main prerequisites need to be fulfilled. First, the geometric conformity has to be assured, i.e. that an edge the belongs to two elements deforms in the same way. Second, the acting outer force $\boldsymbol{F}$ has to be represented by the single forces $\boldsymbol{f}_i$ and finally the deformation energy. If both is true, the overall deformation can be calculated by integrating the deformation of all elements. The time for solving all equations varies due the complexity of the model and can take up to several days.

It has to be clear that a FEA is always an approximation. To get a realistic result, the allowed numerical errors need to be small. On the other hand, the system has a level of complexity that no mathematical solution can be found when parameters are set too strict, i.e. the simulation stops and shows no convergence. Thus, the process of setting up a FEA requires a huge level of experience and should be done by an expert to find the best trade-off between accuracy and a finite calculation time.

4. CONCEPT OF THE VIRTUAL TESTBED IN EROBOTICS

The requirement for an Overall System Simulation is to simulate a real-life scenario as adequate as possible. This means, all different aspects of a system need to be considered, although they are coming from different domains. Especially robots consist of several components emerging from mechanics, electronics, materials science, data processing and many more. Modelling one aspect separated from others may lead to non-realistic results, as the interaction of different component plays an important role. This is especially true for space missions, as there naturally is a lack of adequate experimental test environments. Thus, simulating only parts of a space mission can lead to severe errors.

Consequently, all influences need to be considered in the same framework, which is the main task of an Overall System Simulation. eRobotics is a rather new field of research trying to combine different aspects and thus giving an overall picture [15]. Nevertheless, the environment has a huge impact on the system as well, which is especially true for the harsh conditions in space. The problem is overcome by a Virtual Testbed, which considers the interaction between components as well as influences from the environment [16]. Furthermore, it provides a 3D-visualization making analyses of simulated space missions and the following optimizations easier and more intuitive. Another useful prerequisite is real-time capability, as this allows Hardware-in-the-Loop (HiL) testing.

5. COMPLETION OF THE VIRTUAL TESTBED WITH FEA

As explained, structural effects have a huge impact on an overall system. This is especially true for complex systems under harsh conditions, as it appears in space missions. Furthermore, space technology is dependent on finding new materials to fulfil the increasing requirements. Nevertheless, structural results are only respected in stand-alone analyses. Thus, the next step is to fully integrate FEA in the Overall System Simulation in general. For planning space missions, this means to complete the Virtual Testbed with FEA through a well-designed interface (see Fig. 1).

5.1. Requirements for the interface

For the interaction with FEA, it is crucial, that the advantages of real-time capability, accuracy and usability of the Virtual Testbed are maintained. Two main aspects were identified to meet those requirements when

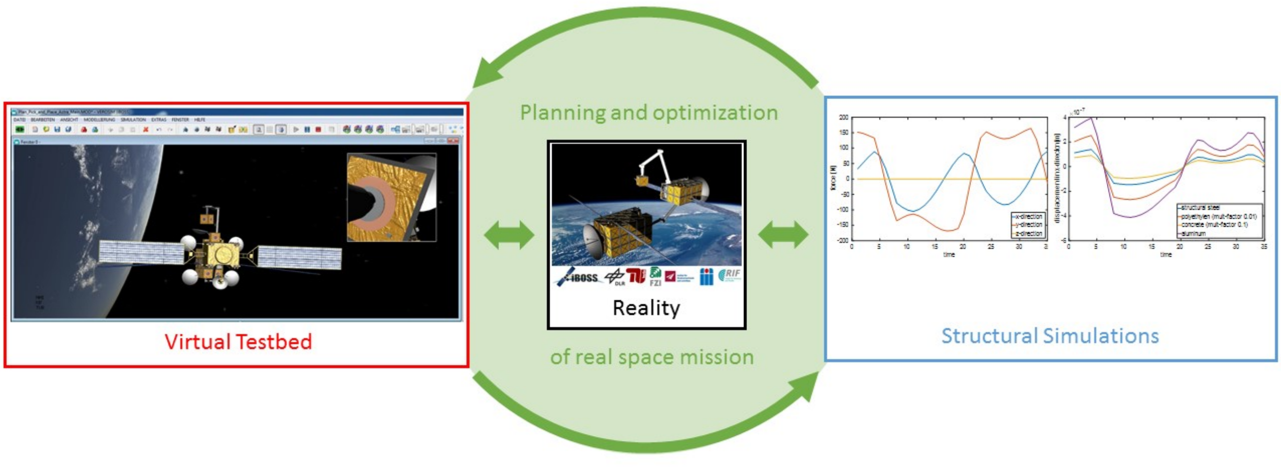

Figure 1: The completion of the Virtual Testbed with structural simulations via FEA allow to model and optimize the real mission before it is started.

integrating structural results.

1. There has to be a separation of expertise. This holds true for the algorithms as well as for the users. As both simulation methods are rather sophisticated and acknowledged, it makes sense to use already existing structures and combine them instead of trying to implement a new overall method. Like this, the accuracy of the methods can be assured on either side.
2. The time-consuming FEA shall only be started on user-request in need. After the request, the interaction has to work completely automated.

5.2. Characteristic variable exchange using joint structures

To meet the second requirement for the interface, the Overall System Simulation has to be the master program during the interaction. The first requirement of separating the expertise and thus maintaining the accuracy for both methods is realized with a variable exchange between the simulation methods. The characteristic magnitudes are given as an input to the other simulation method, i.e. the Overall System Simulation calculated forces and momentums $\boldsymbol{F}$ (further referred to as only "forces"). The FEA uses this forces to calculate the structural deformations (translations and rotations) $\boldsymbol{s}$ and gives them back to the Overall System Simulation to adjust the pose of the RB (see Fig. 2).

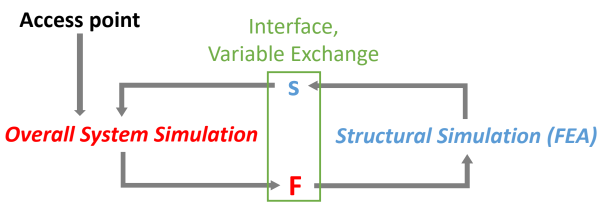

Figure 2: The concept of the interface between the Overall System Simulation and FEA is based on an exchange of the characteristic variables.

In order to do the variable exchange, a so-called "one-side joint" was implemented. It is based on the existing general joint structure in RBD [13], which is e.g. used to calculate the constraint forces $\lambda \cdot \nabla f$ in Eq. 4. Instead of having two RB connected to it, the one-side joint is the link between the rigid part of the model, that stays in the Overall System Simulation, and the deformable part, that is further analysed in the FEA.

6. USING THE INTERFACE

The interface needs to be implemented in an appropriate framework. In principal, the interaction of an Overall System Simulation and FEA can be realized with every software. Nevertheless, there is software more adequate than other due to usability or accuracy. The same holds true for the general workflow: there are several ways of implementing a variable exchange. The focus in this work was set on an automated interaction that is easy to use. This includes a one-time setup procedure for the FEA and several automated modes of operations for the ongoing interaction, which can easily be managed from the Overall System Simulation.

6.1. Software

For the FEA part, ANSYS Mechanical R 16.2 of ANSYS, Inc. Canonsburg, Pennsylvania was used. It was chosen because of its usability, which is enabled via the GUI called ANSYS Workbench. Simultaneously, the solver can be addressed with scripting. This combination allows a one-time standard setup of the FEA with the GUI and an afterwards automated setup out of the Overall System Simulation. Thus, the requirement of the separation of expertise on the one side and an automated interface on the other side can be met.
For the Overall System Simulation, a wide range of functionalities is as important as the framework where the interface is integrated in. To get a Virtual Testbed, a visualization and an easy handling for the end-user is needed in addition. The software VEROSIM fulfils those requirements [17]. It consists of a microkernel, called Versatile Simulation Database (VSD). This central structure provides vital functions as data-management, communication and handling of the simulation models. Its functionality is expanded by extensions, which introduce new features, like simulating sensors, path-planning for robotics or RBD (see Fig. 3). The software is written in C++, so functionalities can be integrated and adapted for certain applications. On the other hand, the GUI allows to operate the software without programming skills. Furthermore, all simulations are 3D-visualized.

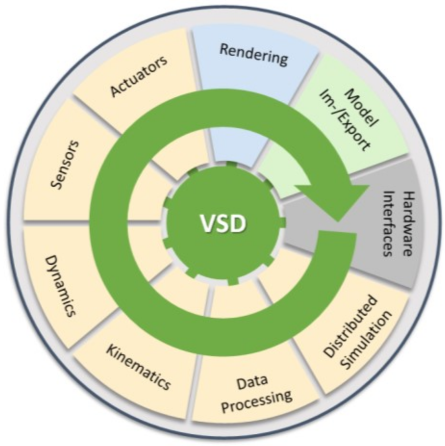

Figure 3: The VSD microkernel structure of VEROSIM allows to extend the functionality of the Overall System Simulation by various important features [17].

6.2. Setup procedure

To integrate FEA, the deformable component needs to be identified in the Overall System Simulation. Thus, the model is divided: the rigid part stays in the Overall

System Simulation, while for the deformable part a FEA is set up. This can be done with the GUI of ANSYS by a FEA expert. After achieving convergence and realistic results, the FEA is prepared for the interaction with the Virtual Testbed, i.e. it is parametrized. This takes about 5 minutes with the help of a manual that was written during this work.
In the Virtual Testbed, the one-side joint is inserted at the division point, where the rigid and the deformable part meet. As explained, the joint calculates the acting forces and serves as the base for updating the pose of all connected RB.

6.3. Modes of operation

On user request, the acting forces can be sent to the parametrized FEA to start a new analysis, which will give the displacement of the deformable component. The user can choose between two main modes of operation, which partly have several options. They are triggered by clicking the associated buttons in the GUI of the Overall System Simulation (see Fig. 4):

1. *DirectFEA*. This mode pauses the RBD and automatically starts a FEA with the acting forces. The displacements at the division point of deformable and rigid part are recorded and directly sent to the Virtual Testbed, where the pose of all connected RB is updated. Then, the Overall System Simulation continues. Thus, in the next time step all structural results are considered explicitly.
2. *LazyModeFEA (LM_)*. The acting forces are saved rather than directly sending them to a FEA. Thus, the time-consuming FEA calculations can be done to a later point in time, e.g. over night. This mode consists of three different options:
    a. *LM_direct*. The acting forces are saved.
    b. *LM_max*. When activated, the maximum forces in each direction are recorded automatically during the whole simulation in the Virtual Testbed. Thus, this option can be considered as a check, whether structural effects play a role in the actual model.
    c. *LM_start*. All sets of saved forces are consecutively sent to the FEA and for each of them, the structural effects are calculated.

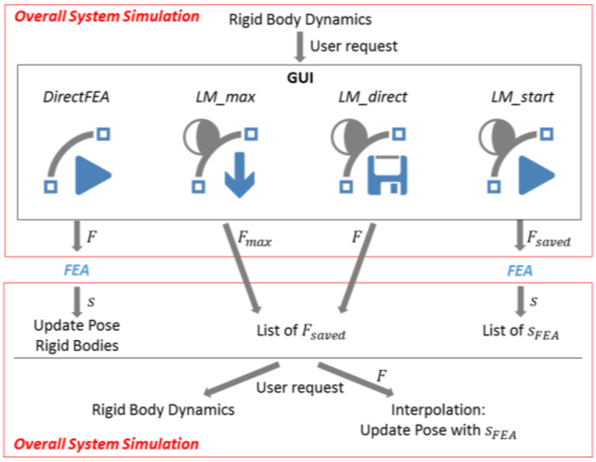

Figure 4: Schematic description of the different modes of operation the user can choose to integrate FEA into the Overall System Simulation.

For every FEA, all resulting displacements are sent to look-up-tables and saved with the forces, which caused them. The interface is completed with an interpolation method. It basically reduces the dimensionality of the mathematical problem and afterwards uses Delaunay triangulation to interpolate a displacement out of given forces. The function griddata of MATLAB by The MathWorks, Inc. Natickk, USA is used right now to check the general functionality of the interpolation.
The use of this method only makes sense if an adequate amount of data from real FEA is present. The data is collected automatically during the usual use of the interface, thus no extra-time has to be taken for that. Although a complete FEA gives a much more precise result, a feasibility study showed that an accuracy of 5% compared to FEA could be reached in 89% of the cases. The interpolation method is much faster than an actual FEA and takes a calculation time of approximately 2-3 seconds, where the starting process of MATLAB takes most of the time.

7. APPLICATIONS

To show the functionality of the developed interface, an example from space robotics is taken. The project iBOSS develops a modular alternative for monolithic satellites, i.e. every functional unit of a classical spacecraft is included in a single block [18]. The general idea is that satellites can be assembled and reconfigured in space, e.g. for lifetime extension or upgrades (see Fig. 5).

Figure 5: Intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly (iBOSS) [18].

Compared to a classical spacecraft, a stabilizing central structure is missing in the building block system. Thus, completely new requirements for the material of the single blocks arise. But even defining those requirements leads to severe difficulties: The forces on the components can be simulated in an Overall System Simulation by acting through different application scenarios. This information helps in lightweight construction to find optimized material parameters for the best trade-off between weight, stability, thermal coefficients etc. The huge problem is that all structural effects will have impact on the load cases again and thereby the original defined forces have to be replaced. This finally creates a vicious circle, as the procedure of updating in every design iteration both on the lightweight construction and on the engineering side is time-consuming and sometimes even impossible.

The developed interaction solves this problem by considering both aspects not only in the same framework, but simultaneously. In the Virtual Testbed with integrated FEA, structural results can immediately be considered during an Overall System Simulation. Thus, for the described application scenario of the iBOSS building blocks a material study was done. In the Overall System Simulation, the reconfiguration of a modular iBOSS-based communication satellite was performed. The satellite already consists of several building blocks and shall get a new functional unit. Thus, it can be considered as the client in this mission. A servicer approaches the satellite and connects with it. It stores the requested new building block and a service robot, which performs the task of reconfiguration (see Fig. 6).

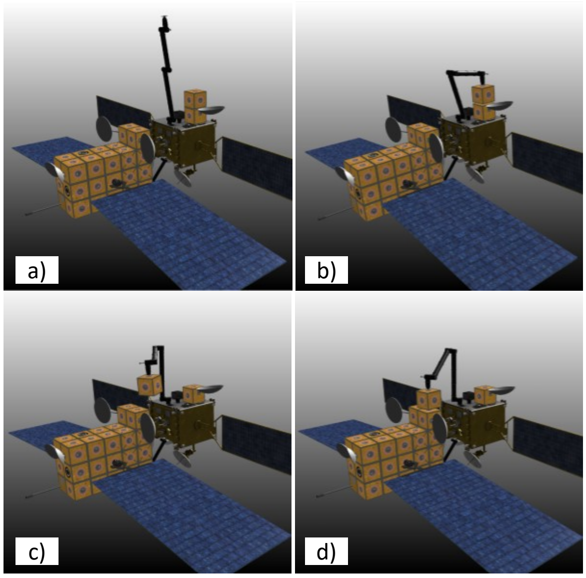

Figure 6: A reconfiguration scenario in a simulated iBOSS mission: The servicer connects to the client (a), the service robot grasps the requested building block (b) and moves it to the appropriate position (c), before finally attaching it to the client (d).

During the reconfiguration scenario, the forces and momentums acting at the division point between the tool center point (TCP) of the robot and the iBOSS building block were recorded. The forces show the expected curve characteristics for a gripping process (see Fig. 7).

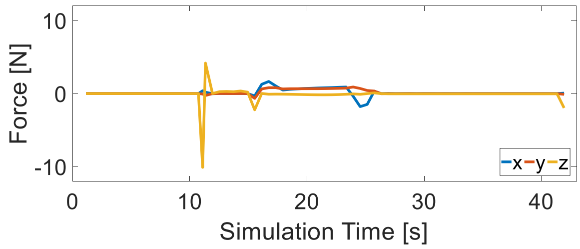

Figure 7: Recorded forces at the division point between the robot and the building block. The z-axis was defined perpendicular to the upper plate of the building block. The gripping itself happens after 11 sec of simulation time, what can be seen in the plotted curves.

The acting forces and momentums were used to perform a material study of the upper plate of the building block, which the robot connects to. In the setup of the resulting FEA, different materials for the plate were considered and the deformations recorded. The results show clearly distinguishable differences between the materials – note the varying scale on the y-axis for polyethylene (see Fig. 8).

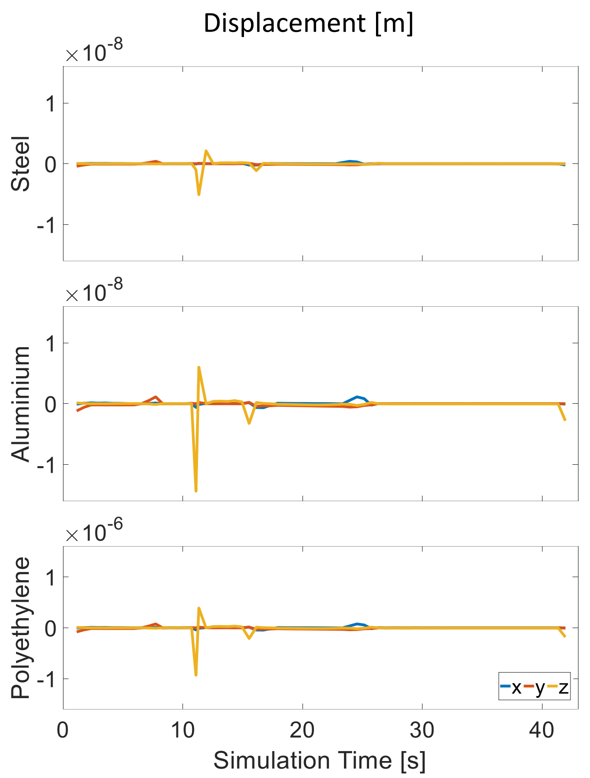

Figure 8: Structural deformations of the upper plate of the gripped building block during a reconfiguration scenario: The feasibility study shows the influence of different materials.

It has to be said that the performed material study was a feasibility study to show the functionality of the interface. The used materials were chosen such that their behaviour under loading conditions varies to prove the usability of the developed interaction. Nevertheless, the implemented separation of methods and expertise allows to do a rather sophisticated FEA including carbon reinforced polymers or other acknowledged materials in the very same way. Furthermore, using the interface the other way round is possible as well: The pose of the TCP of the robot will slightly change during performing the task due to structural deformation of the plate. This can now be included in the Overall System Simulation and thereby the influences are considered in the next timestep in the RBD.

8. CONCLUSION AND FUTURE WORK

In this work, the concept for an interaction between an Overall System Simulation and structural simulations via FEA is developed. The used approach of a variable exchange was implemented in the framework of an existing Virtual Testbed, which was thus completed by structural results. A huge focus was set on an automated interface that at the same time allows a wide range of applications and is easy to use. Furthermore, it was considered that the setup of a FEA usually requires a specialized engineer to guarantee the validity of structural results. Hence, the extension of the Virtual Testbed works in a way that either includes already performed structural simulations or uses a one time validated setup to perform a new structural simulation. Thus, the FEA simulations can be run separately and the final integration of structural results into the Virtual Testbed is done completely automated. This ensures the best possible use of competences on the algorithm- as well as on the user-side. Even more important is the fact that a FEA can be done beforehand and its results are used during the ongoing simulation in the Virtual Testbed. This allows a faster simulation, which comes much closer to real-time capability again.
The functionality of the developed interaction could be illustrated with a sophisticated example from space robotics. The structural deformations that occur during a certain task of a mission were integrated into the Overall System Simulation. This was especially meaningful, as a new modular system for spacecraft was evaluated.
In the future, the functionality of the interface could be further increased by allowing several division points between the deformable and the rigid part of a model. Including the interpolation method directly into the Overall System Simulation code without using MATLAB is interesting as well, both in calculation time as in license issues. Furthermore, more complex FEA should be included in the simulation of real space missions to show the benefit of the developed interaction.

9. ACKNOWLEDGEMENTS

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