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Developing Virtual Testbeds for Mobile Robotic Applications in the Woods and on the Moon

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Abstract — **Simulation in the context of engineering often focuses on very special details of global systems. Robot designers usually begin with the analysis of new actuators and joint designs. This corresponds to a "bottom-up"-strategy in the development of simulation models. For classical fields of application of robotics, e.g. in production plants with a well defined environment this is the approved method, because it allows very detailed insights into the analyzed subsystems. On the other hand, unpredictable effects of the interaction of multiple subsystems may easily be overseen. In particular, non-technical environments like in moon exploration tasks or in a biological environment like in forestry applications are hard to describe in an analytical way to integrate them into an analytical simulation model.**

This is why this paper presents the idea and some practical aspects of the development of "Virtual Testbeds". In a Virtual Testbed, the entire system is simulated as a whole in Virtual Reality – not only small subsystems of a global system. According to the requirements different subsystems are simulated with different levels of detail. In contrast to the classical "bottom-up"-strategy this can be seen as a "top-down"-approach. Therefore the employment of a multi-body dynamics system as a platform for the development of versatile simulation and testing environments is proposed. Using the examples of the evaluation and testing of an extraterrestrial walking exploration robot design and the development of a method for self-localization in forestry, the idea is further deepened. As a special field of attention the integration of a method of soil simulation as a particular requirement of a Virtual Testbed for walking exploration robots is presented.

I. INTRODUCTION

Simulation in the context of engineering often focuses on the details of global systems. For example the design of a new robot often begins with the development of a new joint type and a corresponding actuator. Creation of complex simulation models usually follows this "bottom-up"-strategy: Beginning with simulation models of subsystems, complex simulation models are assembled by putting together the subsystems' simulation models. This corresponds to a "bottom-up"-approach in the creation of simulation models. For classic applications of robotic simulation technologies, for example in production plants, this is a well fitting and approved method. But if technical systems are to be applied in less well defined environments, this approach leads to the weakness of overseen problems arising from unpredictable events or unidentified interactions between the involved subsystems.

This is why recently the concept of "Virtual Testbeds" has aroused some attention. In a Virtual Testbed, complete mission scenarios in close-to-reality virtual environments are simulated as a whole, instead of focusing on a variety of details. If needed, simulation of certain subsystems is refined by specialized simulation models. Thereby designers get the holistic view over a complete mission and detailed insights into special aspects of interest of the mission at the same time.

Examples of simulation systems for robots, which are not confined to an industrial work cell, are the ROAMS Simulation Environment [1], the 3DROV simulation and verification tool [2] or combinations of adapted and integrated off-the-shelf software tools like Matlab/Simulink and SIMPACK as described in [3]. Whereas these are exclusively designed for the simulation of planetary rovers, our goal is to provide a comprehensive simulation tool for various mobile robotics applications.

The paper is organized as follows: Section II presents the idea of a multi-rigid-body dynamics component as a basis of simulation for a variety of Virtual Testbeds. Section III presents some use cases of development and testing in a Virtual Testbed using the examples of a legged robot for lunar exploration missions and a method of self-localization used in the forestry. Because the chosen example of the lunar walking robot puts special requirements to the physical simulation used in the Virtual Testbed, section IV presents a new method for soil simulation and how it is integrated with the existing rigid multi-body simulation system. Finally, section V gives a conclusion and an outlook to future developments.

II. A METHOD OF RIGID MULTI-BODY DYNAMICS SIMULATION AS A BASIS FOR VERSATILE VIRTUAL TESTBEDS

The usability of the "top-down"-approach of Virtual Testbeds for the creation of complex simulation models depends on the availability of a powerful modeling system. Only if new instances of Virtual Testbeds for new applications can be created quickly and efficiently, they can

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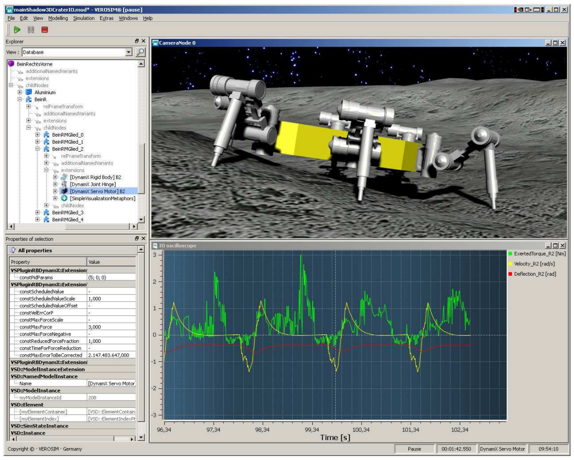
be of great value in different development processes.

As a basis for a modeling system for Virtual Testbeds this paper proposes a rigid multi-body dynamics system. Rigid body dynamics is a well researched field of science and many approaches for a wide range of applications have been presented. We chose a complementarity formulation based on maximum coordinates and Lagrange multipliers. The basics of this approach have been described by many authors, just a view of them are Stewart, Trinkle [1], [5] and Erleben [6]. Efficient methods for solving the resulting mathematical problem of a linear complementarity problem in the context of rigid body dynamics were described by Baraff [8], Erleben [7] and others.

As a platform for the applications presented in this paper, we use the VR-System VEROSIM®. For details of the implementation of the multi-body system itself as well as its integration into VEROSIM®, we refer the reader to [9]. Here are just some facts important to understand the following sections: All features supported by the dynamics kernel are accessible over the user interface via special model-elements, which extend "normal" model-elements by some dynamic functionality. For example a node defining not more than a homogenous transformation and thereby 3 basis vectors can be extended to become a revolute joint by simply adding a "Revolute Joint Extension"-element. This element is extended in the same way with a "Motor Extension"-element, so that both elements together define a motor driven joint.



Property	Value
VSPluginRBDynamX::Extension'	
constPidParams	(5; 0; 0)
VSPluginRBDynamX::Extension'	
constScheduledValue	-
constScheduledValueScale	1,000
constScheduledValueOffset	-
constVelErrCorP	-
constMaxForceScale	-
constMaxForce	3,000
constMaxForceNegative	-
constReducedForceFraction	1,000
constTimeForForceReduction	-
constMaxErrorToBeCorrected	2.147.483.647,000
VSPluginRBDynamX::Extension	
VSD::ModelInstanceExtension	
VSD::NamedModelInstance	
Name	[DynamX Servo Motor]
VSD::ModelInstance	
myModelInstanceId	208
VSD::Element	
[myElementContainer]	[VSD::ElementContain
[myElementIndex]	[VSD::ElementIndexPt
VSD::SimStateInstance	
VSD::Instance	

Figure 1: The workspace of a Virtual Testbed. Robot design by DFKI Bremen [18]

All values calculated within the dynamic simulation kernel, e.g. constraint forces or motor torques are read from or written to a standardized I/O-model. Thereby it is easy to model things like controlling loops or to reuse output values, for example to draw a plot as shown in Figure 1.

III. PERFORMING EXPERIMENTS IN A VIRTUAL TESTBED

This section gives an overview of two successfully applied Virtual Testbeds, both built on the rigid body dynamics core integrated in the VR-System VEROSIM®.

A. *Evaluation of a concrete robot design in a Virtual Testbed*

The first application scenario is the Virtual Testbed used in the "Virtual Crater" research project, funded by the German Aerospace Center [19]. The aim of this project is to find proper methods and parameters for physically based simulations of walking robots for extraterrestrial exploration tasks. This shall be achieved by comparing the results of reference experiments implemented both in reality and in Virtual Reality.

Figure 1 shows a screenshot of the corresponding Virtual Testbed. The widget on the lower left side shows the properties of the component selected in the tree-like view on the data model displayed on the upper left side. The curves drawn in the oscilloscope window are the exerted torque, the angular velocity and the angular value of the second joint of the front right leg of the robot visible in the 3D-visualization.

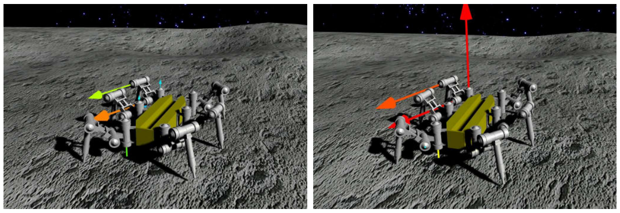


Figure 2: Motor torques visualized within Virtual Reality. Robot design by DFKI Bremen [18]

While the oscilloscope tool is a very classical way to visualize internal values of interest, a Virtual Testbed has the ability to use new and probably more intuitive ways of visualization by offering so called visualization metaphors. As an example, this Virtual Testbed has the feature to visualize motor torques directly within and as part of the 3D-visualization (see Figure 2).

Figure 1 and Figure 2 give a good impression of what a Virtual Testbed offers: Insight into internal processes while the test candidate interacts with a complex, close-to-reality virtual environment with all its imponderables. While the robot tries to accomplish its mission to make his way to a given destination through the virtual environment, the operator has the opportunity to vary the circumstances during runtime. For example he can change the values of the available torques of the actuators or try different walk patterns in a certain terrain. As an example this might help answering the question, if the robot will be able to climb a certain crater rim with less power consuming actuators built in.

B. *Fault simulation in a Virtual Testbed*

With full access to all basic features of a multi-body dynamics simulation core via the user interface, it is possible to perform some simple fault simulations.

Figure 3 shows a sequence of the simulation of a six-legged moon exploration robot. The sequence spans a real-time segment of five seconds. At its beginning the property "constMaxTorque" of the two horizontally oriented motors of the front left leg are changed from "3" to "0" ([Nm]), simulating the total loss of motor torque. The sequence illustrates the robot's reaction to the altered circumstances.

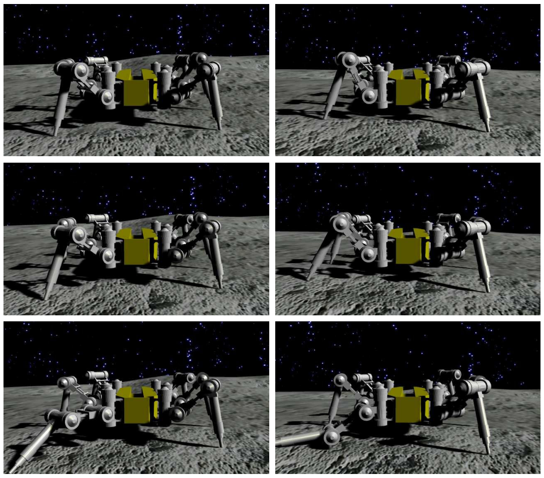


Figure 3: Fault simulation of a six-legged moon exploration robot: Total loss of motor torque in two joints at the front right leg. Robot design by DFKI Bremen [18]

The way this property change is considered within the dynamics simulation core depends on the type of motor that drives the joint. If it is a constrained based motor, which is realized by constraints similar to those realizing joints and contacts, the "constMaxTorque"-property will be used to set the limits for the corresponding Lagrange Multipliers. If the property is even set to zero as done in the example, the corresponding constraint will be completely removed from the system, because a constraint with force limits set to zero will not have any influence on the multi-body system's behavior.

If the motor is a torque-based motor, its torque values are considered as external torques and are now simply limited to zero. Either way, the operator doesn't have to bother about these details, but can focus on his primary engineering tasks.

Another failure type would be the breakage of a joint. This is easily simulated by just dropping the element which extends a leg section to become a joint. This also is done very intuitively at the graphical user interface of the VR-system. Figure 4 shows what happens if a user does so. The sequence spans a real-time segment of ten seconds. The most interesting aspect of this kind of fault simulation in a Virtual Testbed is the fact that the robot will stumble about the lost leg with its other legs. Although this is a very simple example, it demonstrates the actual overvalue of the holistic simulation in a Virtual Environment compared to a detailed simulation of only specific aspects of this system.

A third failure-type is the blockage of a joint. For the purpose of a full blockage joint elements in the simulation model have a property named "isBlocked". Depending on the value of this property, again the constraints implied by that joint will implement a fully rigid connection. Alternatively one could also model a partial blockade using a velocity controlled motor with a constant scheduled value of zero and a limited maximum torque, so that the joint would not be completely blocked but could be moved slightly when undergoing strong external forces.

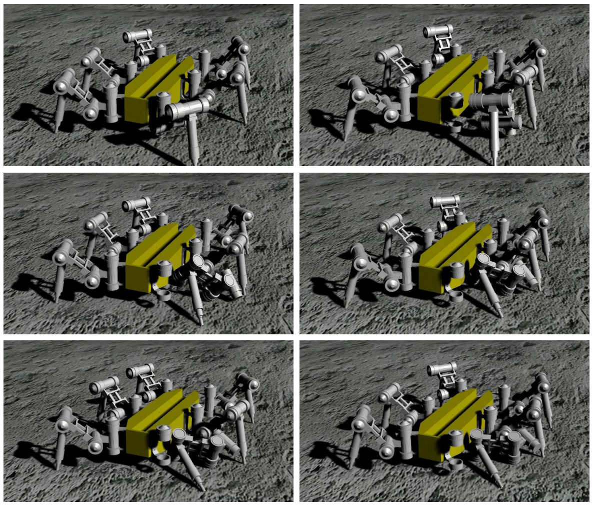


Figure 4: Fault simulation of a six-legged moon-exploration robot: Total failure of a leg-joint. Observe the robot stumbling about the "broken" leg. Robot design by DFKI Bremen [18]

Figure 5 shows the simulation of a complete joint blockage. The vertically oriented joint of the upper middle leg in the first picture of the sequence was blocked at runtime. The sequence spans a real-time segment of 45 seconds. The camera has a fixed orientation but moves with the robot: Note how the robot's walking direction is influenced by one blocked joint.

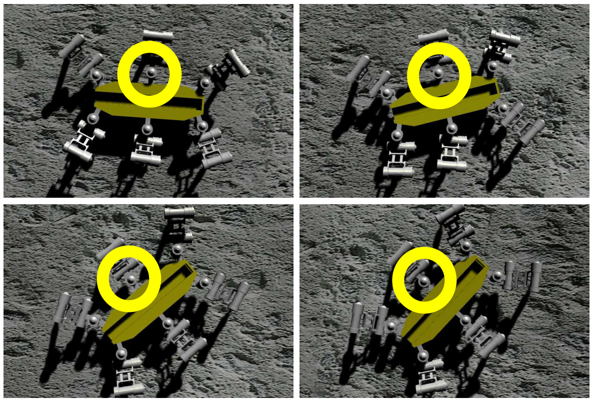


Figure 5: Fault simulation of a six-legged moon-exploration robot: Blockage of leg-joint. The yellow circle marks the blocked joint. Robot design by DFKI Bremen [18]

C. *"Visual GPS": Developing a Method for Self-Localization of Mobile Robots in the Forestry using a Virtual Testbed*

While the two former examples described the application of a Virtual Testbed in a native area of robotic research, the aim of this section is to show the applicability of the approach of Virtual Testbeds in fields of applications, one might initially not associate with robotics.

GPS based localization and navigation in the forest suffers from low position accuracy and even signal loss resulting in wrong position estimations. Therefore a new approach to determine the position of a vehicle was implemented recombining new developments in the field of robotics with methods for single tree delineation.

A simulated wood harvester operated as an autonomous robot is simulated using the multi-body dynamics simulation system. It is equipped with virtual laser scanners to retrieve the required information about its surroundings (see Figure 6). The approach's foundation is a global tree map. To enable the wood harvester to locate itself it has to compare its local tree map with the global one.

The first step is to generate a local tree map from the point cloud data of the mounted laser scanners. Filter algorithms eliminate unusable data such as points at infinity and sparse points to reduce the number of tree candidates. Then a feature extraction algorithm determines tree positions in the local coordinate system of each laser scanner. Combining these tree positions leads to the local tree map of the wood harvester.

A matching algorithm is run based on a tree map, which was generated from remote sensing data, and the tree group, which was detected by one or more laser scanners. Details of this method can be found in [20].

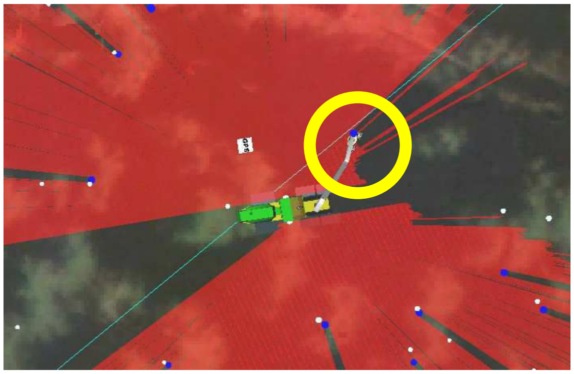


Figure 6: The Virtual Testbed brings up the problem that the harvester's felling aggregate will be disturbing the scanning process.

Major parts of the method were developed just using the Virtual Testbed. Its capability to foresee problems occurring in real environments have already been mentioned. Figure 6 gives another good impression of how this Virtual Testbed helped developers to foresee problems that would have occurred by erroneously detected "trees" resulting from scanning the harvester's own felling aggregate. By using the Virtual Testbed, the problem became obvious when the laser scanners' visualization metaphors were switched on. This helped handling the problem long time before expensive and time-consuming experiments with a real harvester had to be performed.

IV. INTEGRATING OTHER DYNAMIC SIMULATION MODELS INTO A VIRTUAL TESTBED PLATFORM BASED ON RIGID MULTI-BODY DYNAMICS

The basic idea presented in this paper is the "top-down"-approach for the creation of complex simulation models using Virtual Testbeds. For specific applications sometimes refinements of specific aspects of the simulation model are necessary. In the context of moon exploration with mobile robots, the aspect of soil simulation is of high interest. The following sections describe the integration of a soil simulation method with the generic Virtual Testbed framework as an example of the idea of refining simulation models.

A. *A fast method for soil simulation*

The method of soil simulation presented here uses cellular automata as simulation mechanism and is based on the method presented in [15]. For the interaction with rigid bodies, parts of the soil contact model of [16] are used.

The soil surface is described as a height field, i.e. continuous height values on a discrete grid of equidistant nodes (see Figure 7).

Each node acts as a cellular automaton and interacts only locally with its neighboring nodes following a set of rules. These rules ensure a maximum angle of repose and a maximum curvature of the surface. If the gradient between two adjacent nodes is larger than the tangent of the maximum angle of repose, material is transferred between the nodes in order to reduce the gradient. If the curvature along the surface, calculated from the current node and two opposing neighboring nodes is larger than the maximum curvature, the curvature is reduced.

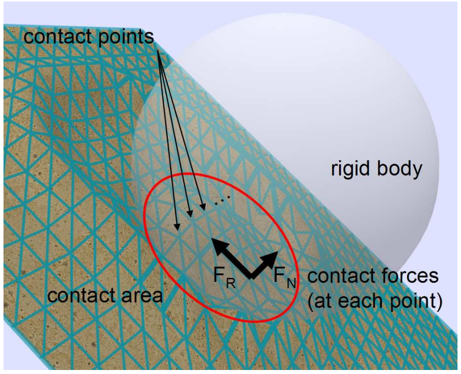


Figure 7: Soil surface described as height field in contact with a rigid body.

The necessary calculations are reduced to a minimum, by maintaining a list of active nodes, whereas all inactive nodes are ignored. This technique was already successfully applied in [17]. If the system is in a stable state, i.e. the required maximum slope and curvature are fulfilled on every node, no calculation is necessary and all nodes are inactive. Only if the system is locally changed from external forces, the affected nodes are activated. If the material content of an inactive node is changed by an adjacent node, it is activated. If an active node is stable, it is deactivated. This implementation is effective with respect to CPU consumption and allows a natural way of parallelization for further performance optimization. External forces can be integrated following [15], by adding a "force equivalent height” to each node, effectively combining the external force and the height differences between adjacent nodes to a single pressure value per node.

The physical behavior of the contact area is approximated by sampling the normal and coulomb friction force at all surface nodes within the contact patch (see Figure 7). These forces are used for the interaction with the rigid body dynamics described in the following section.

B. *A customized Gluing strategy for fast integrated rigid body and soil simulation*

Gluing strategies are known to the dynamics simulation community for a while (see [10], [11]) and seem to be state of the art ([12], [13]). As long as computers and algorithms are far from the ability to simulate comprehensive models of real-world situations on a detailed physical basis like an FEM-approach in real-time, gluing strategies provide a proper way to simulate different parts of a complex simulation with different levels of detail. Gluing offers a simple and physically correct way to interconnect multiple dynamic simulation models and thereby lead to a unique solution of the complete system. This is why gluing is considered as a basic mechanism to combine different simulation models for Virtual Testbeds.

In this section a kind of modified “T-T”-gluing strategy is presented, which enabled the integration of a soil simulation system into the Virtual Testbed for the lunar walking robot.

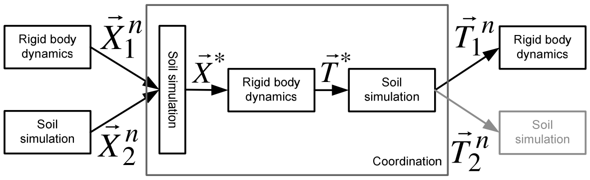


Figure 8: The "Co-operational T-T-gluing-strategy" used to glue together rigid body dynamics and the presented soil-simulation component in a Virtual Testbed.

The soil simulation component takes care of sandy surfaces and calculates plausible or even close-to-reality behavior of the sand. The rigid body dynamics component determines all constraint forces active in a multi-body system and animates the equations of motion undergoing all acting forces and torques. To connect them and thereby become able to find a global solution that meets all conditions from both subsystems, a gluing method is needed. The concrete steps that have to be taken to connect these two subsystems are described in the following enumeration:

1) A collision detection component checks, if a rigid body touches or penetrates the soil surface. If it does, constraints representing a rigid contact between the robot’s feet and the soil surface are added to the rigid multi-body dynamics subsystem.

2) The rigid multi-body system is solved for all constraint forces including the contact normal forces $\vec{T}^*$ (see Figure 8). However, these forces are not yet applied to the multi-body system and the equations of motion are not yet animated.

3) The contact normal forces are delivered to the soil simulation component, where they are interpreted as an estimate of the non-rigid contact normal forces between the sandy surface and the rigid body. The soil simulation subsystem is solved considering the contact normal force estimate, so that it satisfies all compatibility conditions. The result is an updated estimate of the contact normal forces $\vec{T}_1^n$.

4) The updated normal force estimate $\vec{T}_1^n$ is delivered back to the rigid body dynamics subsystem and herein applied as an external force. Then the rigid body dynamics subsystem is re-solved, this time without considering the contact constraints from step 1, since the varied contact normal forces are now applied as an external force.

5) Now all forces within the multi-body system are known and the equations of motion are animated by performing the next integration step.

Figure 9 shows a screenshot of the resulting integrated soil and rigid body dynamics simulation. Compared to the generic T-T-gluing strategy description in [10], this gluing strategy only needs a single iteration to find a solution. This is due to the fact, that the soil simulation component currently is solved in such a way, that it fulfills all compatibility conditions by definition at once. That means it will not detect any penetration after the first iteration by definition. One might say that the soil simulation component is purely reactive within one time step and shapes around the robot’s feet.

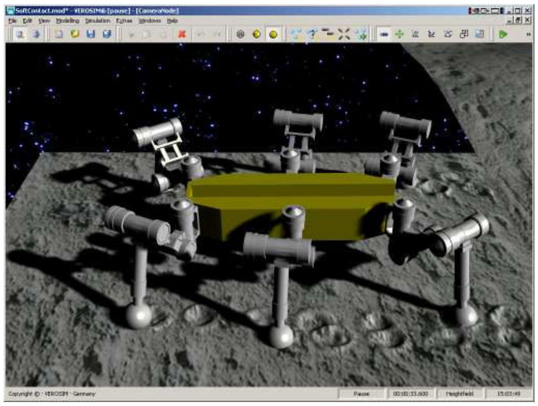


Figure 9: The presented soil mechanics simulation glued to a rigid body dynamics simulation lets the six-legged walking robot walk over deformable terrain in real time. Robot design by DFKI Bremen [18].

Apart from this the gluing strategy can be identified as a classical T-T-strategy. The subsystems are the rigid body dynamics and the soil simulation component. The compatibility conditions $C\left(\vec{X}_1^n(t), \vec{X}_2^n(t)\right) \geq 0$ represent the penetration depth of the feet and the soil surface. What makes this strategy very efficient is the fact, that the coordinator’s tasks are fulfilled by the soil simulation and rigid body dynamics components in cooperation. For a local soil model it is very hard to make a good first estimate of the contact forces, because it has no knowledge about the things "carried by a foot". Therefore the multi-body system is able to offer a good first estimate.

In terms of [5], one might call this a "Co-operational T-T-gluing-strategy". Figure 8 illustrates the idea. Note that in this configuration the soil simulation never reads the $\vec{T}_2^n$ vector, instead the algorithm terminates after the first iteration. However, if the soil simulation system was replaced by another one, the idea of delivering a smart estimate of the contact normal forces from the rigid body dynamics to the soil simulation component can be reused with any other soil simulation model.

V. CONCLUSIONS AND OUTLOOK

In the authors' experience Virtual Testbeds are a key concept to face the challenges of research and engineering tasks in complex, holistic environments. The "top-down"-approach in contrast to the more commonly used "bottom-up"-approach in creating complex simulation models is able to foresee problems developers might face when changing from simulation to reality.

A rigid multi-body dynamics core seems to be an appropriate mediator to realize collaboration of a variety of simulation methods. It offers a promising compromise between computational effort and close-to-reality simulation of physical behavior. Moreover, it is well suited to be combined with other dynamic simulation methods, for example a soil mechanics simulation component as shown in this paper. The integration of other soil contact models, for example the classical Bekker-theory, will be in the focus of future research.

The concept of the holistic approach of the Virtual Testbed is applicable to a variety of areas. Therefore, the approach will be developed further and other simulation components will be integrated. One of those will be physics based, more detailed actuator models, which are of high interest in the context of the "Virtual Crater" project. Such models will help to make precise energy consumption predictions in close to reality mission scenarios.

The authors expect that integrating more and more different simulation models and offering them as tools in a modular modeling environment for Virtual Testbeds will lead to a simulation framework applicable to even more and uncommon areas of application for robotic simulation technologies.

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