A Digital Twin based Approach to Structural Mechanics: New Perspectives for Robotics in Forestry and Beyond

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Abstract: Computational simulations are nowadays crucial for the development of any complex mechatronic system. This holds especially true when it comes to robots acting in a highly dynamic environment, such as robots used as mobile machinery in forestry. The ever changing loads acting on these robots result from different weather conditions, ground stability, leverage forces of falling trees during cutting etc. Thus, the structural layout of the robot is rather sophisticated. Nevertheless, it is usually done once in the beginning of the design process and the dynamic loads can only be estimated, leading to huge safety margins. Regarding the ecological consequences every operation in forestry involves, it is of uttermost importance not only to do a neat structural design, but also to computationally analyse the mobile machinery directly in its actual environment. This work proposes a Digital Twin (DT) based approach to structural mechanics. Every feature of the environment (every tree, the soil etc.) as well as the robot itself can be represented by a DT. An existing Rigid Body Dynamics (RBD) is used to record all acting forces and momentums during an operation. They serve as input for a Finite Element Analysis (FEA) thus enabling a holistic simulation framework.

1 INTRODUCTION

Forestry is an important branch of economics for many countries such as Canada, US, Germany, the Baltic and the Scandinavian countries. While the requirements for improvements in mobile machinery for timber harvesting are the same as for any other robot regarding mechanics, electrics, communication etc., there is one further aspect that needs to be considered and which is of utmost importance: the direct impact on the environment of every work step.

Interesting challenges arise in the mechanical layout of mobile machinery for forestry, as it interacts with an ever-changing and sometimes even “hostile” environment, and – even more important – the ecological consequences of this interaction have to be considered and optimized to sustain a strong, healthy forest for future generations.

While the planning of e.g. thinning strategies and the manual hand-on work is usually done by experienced forest workers who take ecological consequences into account, powerful tools are required to create concrete guidelines further automation can follow to determine specific actions. Thus, using computational simulation is inevitable for improvements in forestry. Nowadays, there are many sophisticated and tested tools to consider both ecological and economical aspects in forestry, some of them even creating a whole “Virtual Forest”.

The design of mobile machinery for forestry (such as harvesters, forwarders etc.) highly benefits from these simulation frameworks, since it reduces otherwise tremendous prototyping costs of any such complex robot with relatively small number of units. Despite the continuous progress in simulation technology, it remains difficult to optimize the robotic layout, as the estimation of dynamic loads is challenging due to e.g. different soil conditions and high leveraging forces of falling trees. Thus, the structural design of the robot is usually still carried out with forces that are assumed to occur during the application and hence have accordingly huge safety margins, leading to unnecessary large weight or limitation in the applications.

This work presents a Digital Twin (DT) based approach to structural mechanics, where structural simulations are performed directly after a work step is executed in the Virtual Forest, where all environmental aspects and different application scenarios may be taken into account. During this process, Rigid Body Dynamics (RBD) calculates the actual dynamic loads serving as an input for a Finite

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Element Analysis (FEA). Following this approach, DTs become the crystallization point in the design and engineering process.

To test this concept, an exemplary application scenario of a harvester cutting a tree was examined (see Fig. 1).

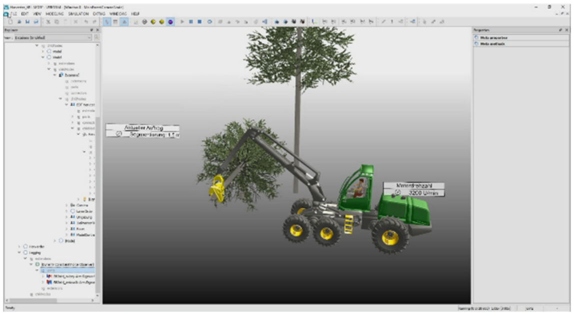

Figure 1: Real-life application scenario for the developed concept and implementation: A harvester is cutting a tree. The DT of the mobile machinery builds the base for enhanced structural mechanics.

2 RELATED WORK

The need for simulation in forestry was recognized many years ago. The improvements in mobile machinery for forestry and the awareness for environmental consequences following their usage grew simultaneously, leading to new thinning and reforestation strategies (Rautio *et al*, 2023). Thus, there are nowadays powerful computational tools to describe forestry processes. The Virtual Forest is one of these concepts. It combines aerial survey technologies, aspects of Virtual Reality and robotics to simulate an actual existing forest and the ongoing forestry in all its facets (Rossmann *et al*, 2009).

Some authors focus on quantifying the economic and ecological consequences of certain forestry operations with mobile machinery (Losch et al, 2017), but a lot of research is done to improve the mobile machinery itself. In (Cheng *et al*, 2023) a more general point of view on agricultural robots is presented, while in (Visser *et al*, 2021) especially automation for harvesting operations is considered, stating that the software requirements for an autonomous felling robot are still in their infancies.

The approach developed in the presented work uses DTs. DTs are seen as a core feature of Industry 4.0, but the general concept has expanded to nearly all engineering applications. The authors of (Negri *et al*, 2017) give an overview of several different definitions of DTs. The way of defining and using them in this work is similar as described in (Atorf *et al*, 2018), where DTs represent their real twins and “are brought to life” by multi-domain 3D simulation systems.

The interaction of RBD and FEA becomes more and more important with decreasing safety margins and complex robots working in highly dynamic environments (e.g. man-machine interaction). Thus there is a wide range of views on this subject: either rather theoretical ones, that deal with the mathematics of coupling (Busch, 2012) and ways of combining the different underlying models (Kaufmann et al, 2018) or approaches being developed for one single application, as “classical” robotics (Chung *et al*, 2010) or automotive engineering (Dietz *et al*, 2001).

3 KEY METHODS

In order to perform structural design for robots used as mobile machinery in forestry, the two principles of RBD and FEA need to be captured by the DT. Both form the mathematical and computer scientific base for this work and thus will be briefly explained in the following section.

3.1 Structural Simulations via Finite Element Analysis (FEA)

FEA is a validated and sophisticated method for structural mechanics, described in many textbooks, e.g. (Bathe, 1996). External influences serve as input variables (forces, temperature, etc.) in order to calculate the behaviour of the structure (deformations, stresses, temperature distributions, etc.) as output variables. The material and the shape of the examined structure set the relation between both.

First, the structure is meshed and hence mathematically discretized, i.e. divided into m individual elements. Nodes connect these elements. During the so-called preprocessing, boundary conditions (BCs) are defined in the form of loads and supports. The next step of solving describes the solution of the mathematical problem, which can be simplified as follows:

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

Here, u_i describes the displacement of the elemental nodes of element i, $\boldsymbol{f}^i$ is the corresponding acting force and the matrix entries $\boldsymbol{k}_i$ reflect material-specific elastic moduli. In descriptive terms, during the solution, all external acting forces must be translated into deformations, while the nodes couple neighbouring elements to move accordingly. Thus, a system of coupled differential equations is created, which in general cannot be solved analytically. The crucial parameters for numerical solving have also been specified during the preprocessing (required accuracies of the solution, termination criteria, etc.). Depending on the complexity of the model and the computing power used, the calculation of the solution requires a few seconds up to several weeks.

Afterwards, the results can be visualized and analysed in the subsequent postprocessing.

3.2 Rigid Body Dynamics (RBD)

The simulation of RBD is a well-established tool for the development and analysis of mechanical systems. Depending on the use case, several approaches like the Composite-Rigid-Body Algorithm (generalized coordinates) (Featherstone, 2012) and the $JMJT$ approach (maximal coordinates) (Baraff, 1996) are applied. RBD aims for a macroscopic simulation of the system, replicating the kinematic and dynamic properties of the system. In addition, several extensions to RBD exist, allowing for a simulation of deformable objects and compliant mechanisms (Bender et al, 2014). The approaches are capable of visually replicating structural deformations but are not yet sufficient for the realization of high-fidelity DTs, since the fundamental models are just simplifications of the structural properties of the bodies and do not provide the required level of detail.

The envisaged coupling of RBD with detailed FEA poses some requirements on the pursued RBD simulation approach. The RBD simulation must allow for detailed introspection capabilities in order to capture the bearing forces within the system, which will then be passed to the FEA simulation. Additionally, the implicit interaction of a DT with its environment must be possible, setting this DT-based approach apart from other simulation approaches like Modelica or Simscape. (Both only allow to describe the explicit interaction – e.g. joints – between bodies. Collisions have to be modelled explicitly, which is not feasible for DTs interacting with complex environments.)

Consequently, we build upon a rigid body simulation in maximal coordinates, following the $JMJT$ approach. The kinematic constraints are described by position-based constraints C and are implemented by the constraint Jacobian $J = \partial C / \partial x$, forcing the relative velocity of two connected rigid bodies at the joint position to zero, see (2).

$$J \cdot \dot{x} = 0 \qquad (2)$$

This way, complex systems can be described easily. For each joint within the system, additional lines are added to the Jacobi matrix J. Based on the kinematic constraints captured by the Jacobi matrix J, the constraint forces λ can be calculated by an impulse-based approach (Stewart *et al*, 2000), see (3).

$$\begin{gathered} \mathrm{JM^{-1}J^{T}} \cdot \mathrm{dt} \cdot \lambda + \\ \mathrm{J} \cdot [\dot{\mathrm{x}} + \mathrm{M^{-1}} \cdot \mathrm{dt} \cdot \mathrm{f_{ext}}] = \mathrm{b} \end{gathered} \qquad (3)$$

The mass matrix is described by M, the external forces (e.g. gravitation) are described by f_{ext} and finally the vector b is used for stabilization purposes (Baumgarte, 1972).

The interactions of the DT with its environment (i.e. contact forces and friction) are realized based on complementarity constraints, resulting in a Linear Complementarity Problem (LCP) (Anitescu *et al*, 1997). Therefore, a slack variable a is introduced to the right side of (3), allowing to formulate the complementarity condition (4).

$$a \geq 0 \;\;,\;\; \lambda_{contact} \geq 0 \;\;,\;\; a \cdot \lambda_{contact} = 0 \qquad (4)$$

Either two colliding bodies are separating ($a > 0$) and no contact force needs to be applied ($\lambda_{contact} = 0$), or a contact exists ($a = 0$) and a contact force prevents penetration of both colliding rigid bodies ($\lambda_{contact} > 0$).

The final building block in the RBD tool chain is the handling of kinematic loops. Kinematic loops introduce redundant constraints to the simulation, resulting in a reduced row rank of the Jacobi matrix J. Consequently, the system matrix $A = JM^{-1}J^{T}$ becomes singular and (3) will not have a unique solution for the constraint forces λ. In order to cope with such singular systems and achieve an unambiguous solution for the constraint forces λ, a Constraint Force Mixing based regularization of the system matrix A is performed (Smith, 2019). Subsequently, a small amount of compliance is introduced to the simulated system that can be controlled by the magnitude of the regularization parameter, resulting in an efficient calculation of the inverse dynamics problem.

Once the constraint forces λ are calculated, the forward dynamics can be solved.

$$\mathrm{M} \cdot \ddot{\mathrm{x}} = \mathrm{f_{ext}} + \mathrm{J^{T}} \cdot \lambda \qquad (5)$$

Applying this simulation approach allows to efficiently analyse the dynamic loads occurring when a DT interacts with its environment. The introspection to the bearing loads is given by default and thus allows to effortlessly generate the required inputs for a detailed FEA of arbitrary structures within the DT.

4 CONCEPT: ENABLING A HOLISTIC SIMULATION FRAMEWORK

Every single operation in forestry (such as cutting a tree, reforestation, etc.) is subject to a forestry plan. In this way it is ensured, that both economic and ecological aspects are taken into account. The different work steps are favourably done with mobile machinery, whose structural design has been defined with the help of FEA (see left side of Fig. 2). Today, there are sophisticated simulation methods to examine the outcome an operation will have and thus to estimate its economic and ecologic consequences. As both the robot itself and the environment are rather complex and highly interact with each other, there are many different aspects to consider. Thus, all of them and their connections should be represented virtually, creating a whole “Virtual Forest” (Rossmann *et al*, 2009). Every part of the system gets a DT. This holds true for e.g. every tree, the ground, stones, the forestry workers, and of course the mobile machinery. With this, one can answer specific questions (e.g. “Is it possible to cut this tree if the harvester is in this position?”) and develop whole forestry strategies (e.g. “If we want our forest to have this structure and tree assortment in X years, what do we need to do now?”).

Nevertheless, this already very elaborated picture is still missing a direct link to the structural design of the deployed robots. In general, the structural layout of a robot is created with the help of FEA. The forces and torques required to perform a structural analysis are usually estimated or based on real life experience of other structures. But the loads in a forest are highly dynamic, due to weather conditions, leverage effects of falling trees, ground stability etc. The ultimate value for structural design is the safety for the present forestry workers and the durability of the robot.

Thus, a neglect of structural analyses for an individual operation leads to omission of possibilities on the one hand (“this tree could have been cut, as the estimated leverage effect was to high due to its actual shape of the treetop”) or a to high ecological impact on the other hand (“the used mobile machinery could have been way lighter, thus the soil is unnecessarily compressed”).

In this work, a concept was developed to do a more flexible and neater structural design, as RBD is performed for the DT of the mobile machinery and the recorded loads serve as input for a FEA. Thus, a holistic simulation framework is enabled.

As the actual dynamic loads are considered, this builds a solid foundation for optimizations (of the robot and work processes) and finally even automation, as specific instructions for every situation can be defined from the holistic simulation framework (see right side of Fig. 2).

Please note, that the general concept also holds true for completely different fields of application, where complex robots encounter highly dynamic environments (such as robots collaborating with humans or space robotics).

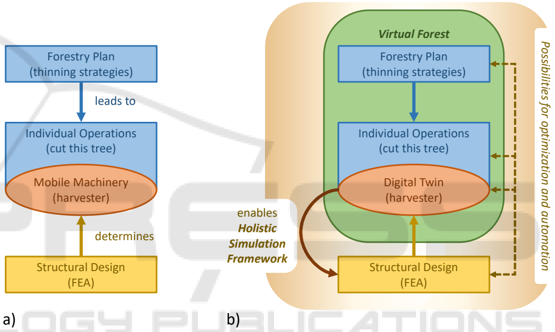

Figure 2: Comparison of a classic sequential design and engineering process for forestry (a) and the developed interlaced concept building on DTs and a Virtual Forest (b): usually a forestry plan leads to the individual operations, which are performed with mobile machinery. The robots were developed beforehand, where the structural design was based on assumptions (a). There already exist elaborated simulation tools to virtually represent this workflow: the mobile machinery is represented as DT in the Virtual Forest. The new concept adds structural design to this scheme (left side of b)), thus enabling a holistic simulation framework, which finally allows to do optimization and automation (right side of b)).

5 REALIZATION VIA A DIGITAL TWIN (DT)

In context of this paper, we present an in-depth analysis of a harvester that is used to cut and segment trees in forestry applications. The analysis is focused on systems level mechanical aspects and detailed structural analysis of selected elements. We created a virtual test scenario that highlights the interaction of the harvester with its environment (i.e. cutting trees).

The DT of the harvester is shown in Fig. 3. It consists of a detailed RBD model that models the relevant parts of the harvester. The mechanical model is parametrized according to estimated masses and information provided by CAD data. The kinematics of the crane and harvesting head are also extracted from CAD data. Since we are not interested in the hydraulic design of the crane, we can neglect the hydraulic aspect in the DT and approximate the hydraulic cylinders by two actuated rigid bodies. In addition, we did not model the actuators based on external forces f_{ext} but based on constraints $J \cdot \dot{x} = v_{target}$ imprinting a desired velocity v_{target} to the system. This way, it is easy to realize desired motions of the crane without the need to emulate the control software, leading to a more efficient DT.

Figure 3: DT of a Harvester.

Since the mechanical stresses in the telescope arm are expected to cause the most structural stress on the crane, we decided to analyse these stresses in detail. Therefore, the bearing forces and torques are measured in a RBD simulation and are injected to the FEA at defined injection points, as shown in Fig. 4. We intentionally realized a unidirectional coupling, since the expected deformations will be very small, and the material will either withstand the mechanical loads or burst entirely. This way, complex and computationally demanding bidirectional coupling between RBD and FEA can be avoided.

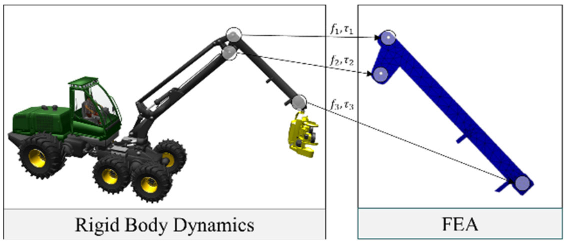

Figure 4: Interface between RBD Simulation and FEA Simulation.

In addition to the DT of the harvester, we realized a DT of a forest environment (as shown in Fig. 5). The Virtual Forest is built from GIS data. In the direct neighbourhood of the harvester, the trees have been replaced by their DTs, meaning that they include a full RBD model approximating their collision shape and mass distribution. The interaction between the harvesting head and the trees is described by a spring-damper model with Coulomb friction, approximating contact and friction forces. Additionally, the ground contact of the harvester is modelled by individual spring-damper models and Coulomb friction allowing to roughly estimate the mechanical stress to the soil surface.

By fusing all DTs in a holistic scenario, we are able to simulate the interaction of the harvester with its environment via contact forces and friction. This way, the dynamic loads that occur during cutting a tree can be simulated and predicted easily. Emerging from these DTs, we are able to realize the intended application.

6 EXAMPLE APPLICATION SCENARIO: DISPLACEMENTS ON CRANE DURING HARVESTING

In order to test not only the DTs, but also the whole concept, a specific application scenario was chosen. As it is displayed in Fig. 5, the harvester is cutting and segmenting a tree in the holistic simulation framework.

Figure 5: DT of a harvester in a forest environment cutting a tree.

Fig. 6 shows the forces and torques calculated by RBD on the top end of the last crane arm segment, which were taken as input for the FEA (see Fig. 4).

Several points of the recorded curves (green arrows in Fig. 6) can be assigned clearly to specific work steps of the task shown in the lower row of Fig. 7. First of all, there is a time span without any recognizable forces on the crane arm, when the harvester is moving to a suitable position for cutting the tree (point 1 in Fig. 6 and Fig. 7). Then there are two force peaks: one, when it's connecting to ("hitting") the tree and the second one, when the cutting is done and the tree falls over (point 2). This is where a huge torque is starting to be recorded, as the tree is now hold horizontally by the harvester. During the segmentation process, this torque (and the force) declines, as the leverage effect decreases with an ever shorter tree trunk (point 3).

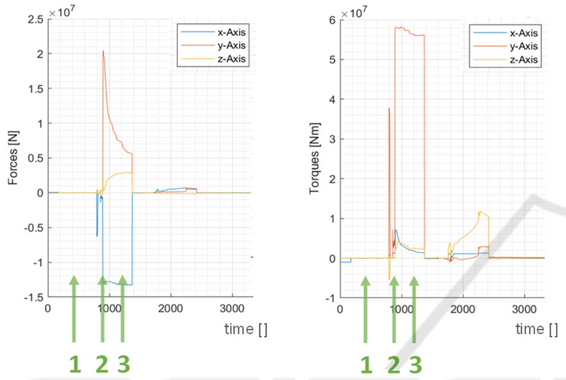

Figure 6: Recorded forces and torques for joint 1 during the performed task of cutting and segmenting a tree. (The x-axis is displaying simulation time and therefore without a unit). The green arrows mark specific points in time (see Fig. 7).

As expected, the deformation of the crane arm segment behaves accordingly (upper row of Fig. 7) with no deformation without force (point 1), a deformation peak at point 2 during the cutting and a slightly deformation during the segmentation process (point 3).

It has to be clarified again, that this application scenario is exemplary and e.g. no hydraulic effects were considered, thus the results of the FEA are qualitatively right, but cannot be quantified. Nevertheless, if the missing information is provided (e.g. by the manufacturer), this can be easily implemented. This is another advantage of the realization via DT, as the same model gets more and more sophisticated while using the same holistic simulation framework.

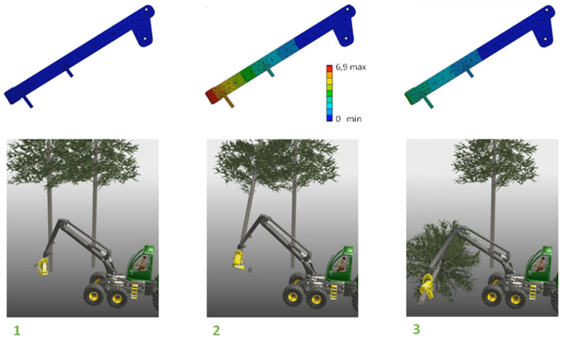

Figure 7: The upper row shows different deformations of the crane arm. As this was an exemplary study, the results are qualitatively and not absolutely. The time points 1, 2, 3 from Fig. 6 can be directly assigned to characteristic actions of the harvester and the resulting deformations of the crane.

Furthermore, it is even possible to focus on different aspects of the Virtual Forest in this small example: from an ecological point of view, the impact on the environment might be analysed as compression of the ground or destruction of the undergrowth. On the other hand, for economics, it might be interesting to collect all information about the cut tree or to examine, whether a neighbouring tree was damaged during the process. The respective focus can be easily analysed by choosing different visualization styles, while the underlying simulation stays the same: e.g. Fig. 5 for the ecological point of view and Fig. 7 for the economic one.

7 CONCLUSION

In this work, a holistic simulation framework was enabled by taking a DT based approach to structural mechanics. This concept leads to a more profound structural design of robots in highly dynamic environments, as the underlying FEA may be performed directly after a certain operation is done virtually. This is achieved by creating DTs of the robot itself and the whole environment and calculating the explicit forces acting on the robot with the help of RBD.

Especially in forestry, neat structural layout is crucial, as any operation with mobile machinery has not only economic consequences, but might have a huge ecological impact as well. Thus, in this work, the developed concept was directly interlaced with a Virtual Forest and an exemplary application scenario of a harvester cutting and segmenting a tree was successfully performed.

8 OUTLOOK

In future work, the execution of the developed concept could be automated and – subject to the condition that required computing time and hardware is available – made bidirectional concerning RBD and FEA. This would allow to perform parameter studies, do even more sophisticated optimizations or to integrate continuative concepts such as structural health monitoring.

Even more important, there will be a sophisticated test of the presented work during an upcoming project. The involved industry partner will build a completely new type of harvester crane and its structure is designed with the help of the developed holistic simulation. As all preliminary work is done, real life data (exceeding simple experiments) will directly be used to further analyse this ansatz, quantify its limits and validate the concept and implementation in general.

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