Developing an Experimentable Digital Twin of a Novel Forestry Machine: Application, Experiences, and Benefits

SEBASTIAN SCHMID, ULRICH DAHMEN, LONGXIANG SHAO, KAI-UWE SCHRODER and JURGEN ROSSMANN

ABSTRACT

The forestry sector in central Europe aims for a fully mechanized wood harvest. This goal is currently restricted by the limited reach of forest harvesters on the market and legislative specifications on the distance between skid trails. As a consortium of industry and academia, we are developing a novel forestry machine that is designed to fell and skid trees in the inter-field between skid trails and which is equipped with a lightweight boom for an extended reach; to date, felling in the inter-field is not reachable for harvesters and is done in manual labor. As a key risk, overturning the whole forestry vehicle prevents a transfer of current harvester designs to an extended reach. To avoid overturning, we apply a consequent lightweight design for the boom of the new forestry machine. The development of the forestry vehicle will be supported by a versatile use of Experimentable Digital Twins (EDT), which are one promising concept to push the idea of Digital Twins into practice. The EDT allows for interaction in a pure virtual or in a hybrid environment. The tasks of EDT in the context of the new forestry machine will include a virtual prototype in the development phase, a driver assistance system in the operational phase, and a central hub for a strain-based monitoring system in the operational phase. This contribution gives an insight into our present work on the EDT of the novel forestry machine, emphasizing the load monitoring system of the lightweight boom. On a conceptual level, we present the load monitoring system, addressing the challenges specific to this application. We outline the proposed strain sensor distribution and describe the interaction with the EDT.

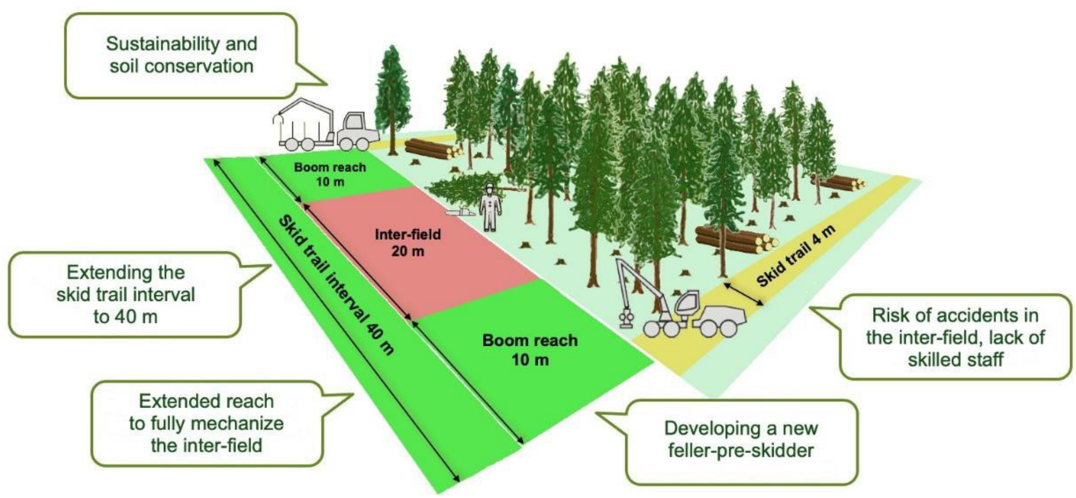

Figure 1. The novel forestry machine is designed for felling and skidding of trees in the inter-field.

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INTRODUCTION

In recent years, Central European silviculture has witnessed an increasing focus on achieving sustainability goals, encompassing economic, social, and ecological aspects [1]. As a project consortium of industry and academia, we are creating a novel forestry machine specifically designed to enable a fully mechanized wood harvest to support achieving these sustainability goals. Figure 1 shows the difficulty in the current Central European wood harvest: For ecological reasons, legislative regulations aim for uneven-aged silvicultural management with mixed populations of broadleaved and conifer trees and additionally, intending to protect the forest soil, demand a distance of 40 m between skid trails. With conventional harvesters reaching 10 to 12 m, this leaves an inter-field of ca. 20 m to be harvested in manual labor, a hazardous work that to-date suffers from a lack of specialists. A fully mechanized wood harvest will bring in line the ecological goal of soil conservation with social goals of on-the-job safety of workers and, lastly, with the economic goal of cost-reduction for forest businesses.

In our concept, a novel forestry machine is designed to fell trees in the inter-field and skid them into the reach of conventional harvesters, moving on the same skid trails as other forestry vehicles. The feller-pre-skidder vehicle is shown in Figure 2. It is equipped with a lightweight crane boom for an extended reach, a feller grapple, and a winch for skidding. The 20 m crane boom creates problems in terms of overturning of the vehicle and maneuverability in a dense forest. Due to overturning, a simple extension of the conventional harvester design to 20 m reach is not applicable. To avoid overturning for the feller-skidder vehicle, consequent lightweight design is applied for all extendable parts of the machine: the feller grapple, the crane boom, and a driver assistance system to address the problems that result in the use of a 20 m crane boom in a dense forest.

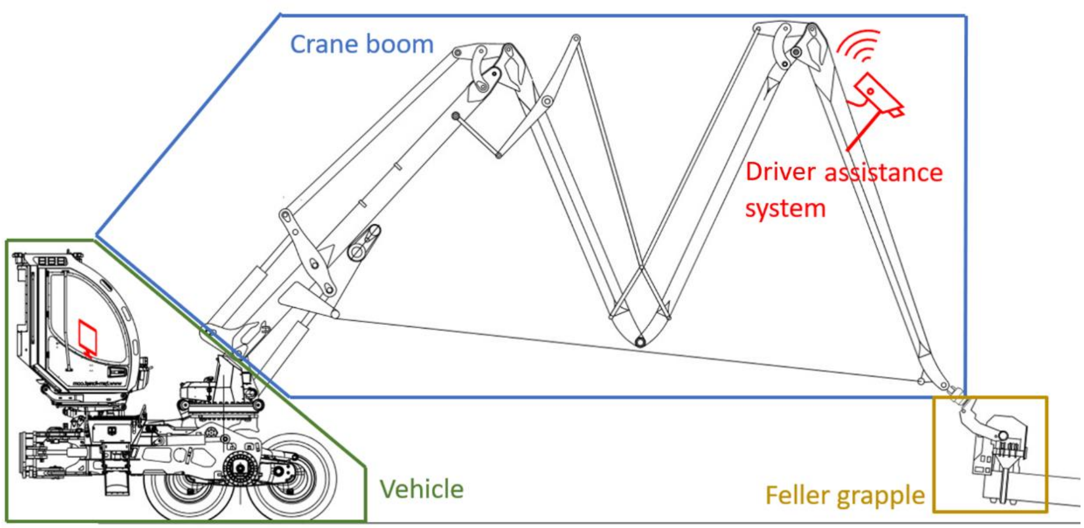

Figure 2. The overall system “feller-skidder vehicle” with its four main subsystems: vehicle, crane boom, feller grapple, and driver assistance system. [2]

Our project involves building an EDT for the feller-skidder vehicle. EDTs are virtual digital representations of physical entities using experimentable models to simulate their structure, functions, and communication with the environment, for example, in a multi-body dynamics simulation [3, 4]. The tasks of the EDT in the context of the new forestry machine will include serving as a virtual prototype in the development phase, a driver assistance system in the operational phase, and a central hub for a strain-based structural monitoring system in the operational phase. In general, an EDT consists of three algorithm blocks: the simulated technical assets, the simulated data processing system, and the human-machine interface, all of which are connected through a simulated communication infrastructure. By implementing an EDT for this forestry machine, we can simulate its interaction with the environment and optimize its performance before physical testing occurs.

In recent years, several studies have investigated structural monitoring systems for heavy equipment vehicles. SHM systems were implemented by Barat et al. for a walking dragline excavator using the acoustic emission method [5], and by Misiewicz et al. for a bucket wheel excavator joint using thermoelastic stress analysis [6]. Peng et al. proposed a load monitoring system for an excavator that associated sensor data from hydraulic cylinder pressure and displacement with kinematic and dynamic simulations to characterize impact loads [7]. However, the use of EDT in structural monitoring of heavy equipment vehicles has not been addressed, and in our work, we intend to address this gap with the example of the feller-pre-skidder vehicle.

EDT OF THE NOVEL FORESTRY MACHINE

Virtual Prototype in the Development Stage

The project consortium is building a comprehensive EDT of the overall system “novel forestry machine” for application as a virtual prototype. Along the same lines as a real prototype, the EDT contains all essential functionalities of the entire system, and it is used to gain a deeper insight into system parameters, to validate the concept of the novel forestry machine, and to make a virtual comparison of design and process options. The virtual prototype was first drafted as a model-based system engineering model in the Systems Modeling Language, and it consists of four main subsystems, which are the vehicle, the crane boom, the feller grapple, and the driver assistance system (see Figure 2). Essential functionalities include vehicle and crane boom dynamics, crane boom and feller grapple hydraulics, as well as sensor data collection and processing.

The capabilities of EDT are extensively used to support the design and sizing of structural components of the lightweight boom. The simulation framework, in which the virtual prototype is tested, provides insights into the system parameters that are difficult or impossible to gain in a real prototype, for reasons such as availability of

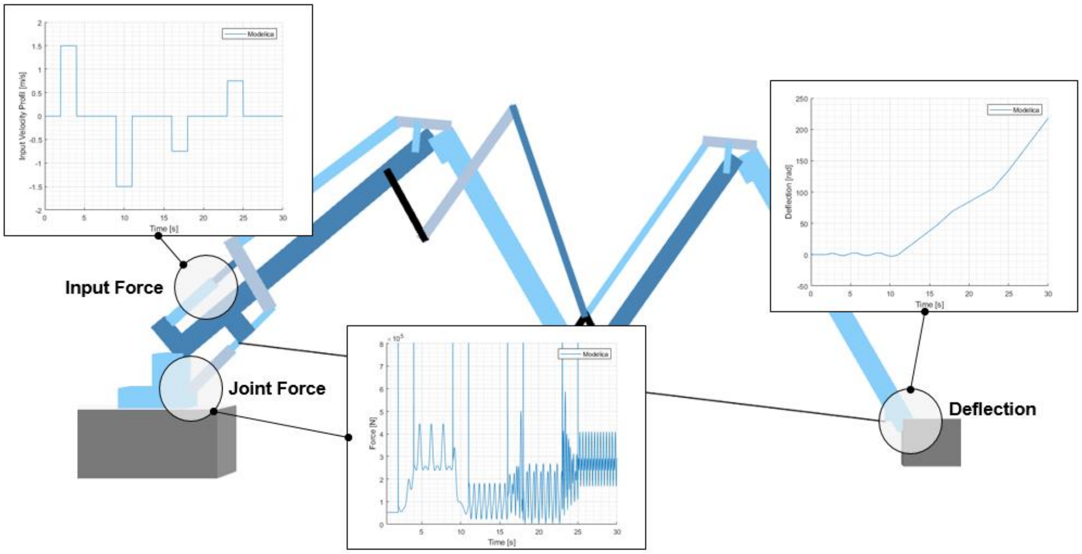

Figure 3. Load values derived from the investigation with the help of EDT.

measurement equipment or risks to the driver, the environment or the machine itself. System parameters related to the design of structural components, such as joint forces, accelerations, and external loads, are collected and summarized as load spectra in various scenarios. These load spectra are used as the basis for structural design with structural simulation software, such as the Finite Element Method. Figure 3 shows the load values extracted from the investigation of the lightweight boom by building an EDT of the novel forestry machine.

Another use of the virtual prototype is the simulation-based testing of the overall feller-pre-skidder vehicle concept in order to avoid unexpected behavior after manufacturing the real prototype. The behavior of the novel forestry machine is analyzed in silvicultural systems with different properties, such as tree density, tree type (broadleaved vs. coniferous forests), and terrain slope. Also, the different positions of the remaining trees, which represent obstacles to the machine, are investigated. We perform simulations in virtual testbeds that are populated with virtual forests. Besides the forest, the feller-pre-skidder vehicles also varied: parameters, such as crane length, control parameters, hydraulic pressure, etc., are adjusted and tested. The same holds for the evaluation of felling and skidding strategies which are tested for their impact on the environment. In a further development stage, the simulation-based testing in virtual testbeds will be carried out interactively with a driver who operates the machine with a joystick. The subjective impressions of professional drivers in an immersive experience will allow for a better evaluation of the overall vehicle concept.

Driver assistance system in the operational phase

The length of the crane boom limits the driver's perception around the crane tip. It thus leads to difficulties for the driver in situational awareness and maneuverability of vehicle, crane, and feller grapple. The number of obstacles in the line of sight between the driver and the feller grapple increases while the driver's depth perception through binocular vision diminishes. To assist the driver with these difficulties, we are implementing a driver assistance system supported by the human-machine interface of

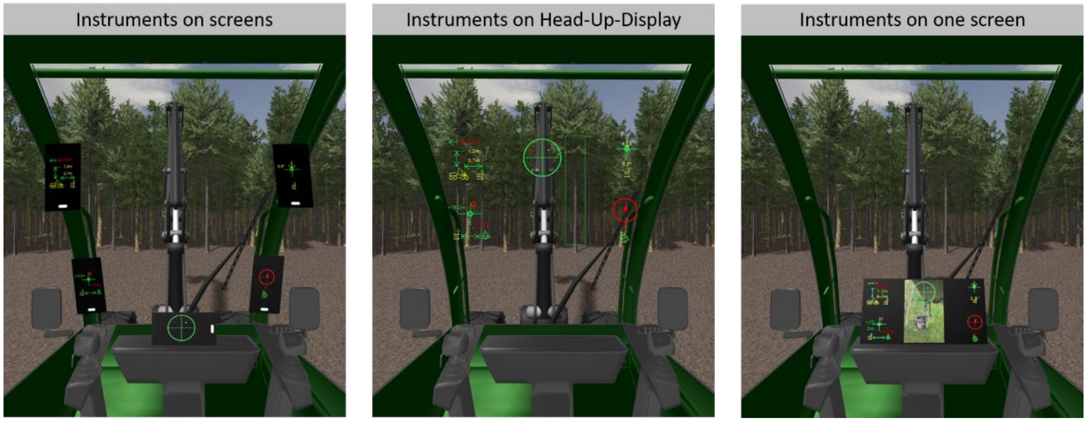

Figure 4. Possible configurations of driver assistance system's human-machine interface.

EDT. Through a human-machine interface, the information collected by the sensors and processed by the EDT can be displayed to the driver. Figure 4 shows some display options that are currently discussed.

There are three most important types of information transmitted and visualized by the human-machine interface: the spatial position and orientation of the feller grapple relative to vehicle and target tree; the spatial position and orientation of the crane boom relevant to assessing the stability of the vehicle; and the detection and highlighting of previously selected and marked trees.

During the development phase, we evaluate different approaches to the driver assistance system in a virtual testbed. This includes the collection and processing of virtual sensor data, i.e., the simulation of camera, lidar, or radar images. With this information, we analyze and find the appropriate positions of the sensors in different scenarios.

LOAD MONITORING SYSTEM OF THE LIGHTWEIGHT BOOM

In our implementation of a monitoring system for the lightweight boom, we deliberately decided to prioritize a pure load monitoring system over an SHM system. This decision is based on several reasons:

- Availability is not a critical requirement: Forestry machines are not fire trucks, i.e., the consequences of unplanned downtime are mild.
- Structural failure is not catastrophic: A safety perimeter of a 70 m radius for felling operations is established either way, and the driver's cabin is designed to resist the strike of trees that are much heavier than the crane boom.
- Cost-effectiveness: As structural elements are accessible without greater effort for visual inspection, the initial cost of an SHM system is unlikely to be amortized.

Nevertheless, an SHM system might come into question for future vehicle generations when a better understanding of fatigue hotspots is available. Through the load monitoring system, we intend to leverage capabilities provided by EDT to create the following main benefits for vehicle operators:

- Continuous comparison of actual loads with design loads: The load monitoring enables the operator to continuously update the actual load history on the crane boom, which is a prerequisite for estimating the remaining service life of the structure.
- Direct feedback to the driver: The load monitoring system provides the driver with direct feedback regarding the impact of felling and skidding operations on the machine's structural life. Feedback is provided via the same human-machine interface as the driver assistance system. The driver can adjust his working skills to minimize structural wear and tear by receiving real-time information on the costs associated with specific actions. This feedback mechanism helps improve operational efficiency and reduce unnecessary structural costs.
- Evaluation of the EDT: The load monitoring system provides valuable information to assess the validity of load spectra generated by the EDT during the design phase.

Several challenges arise while developing a load monitoring concept for the crane boom. For example, loading conditions are uncertain, as loads are not only introduced at the connection to the feller grapple but also from slewing movements and contact with undergrowth. Another challenge is the rough environment that threatens to damage any sensor and interface hardware.

Proposed Load Monitoring Concept

We propose to supplement existing sensor resources, such as pressure and displacement sensors, with strain sensors at locations with well-determinable load states and combine this sensor network with a data-based approach to identify typical load cases and their structural costs. As some components of the beam structure have complex load states, such as combined unsymmetric bending and torsion, measuring all section forces and moments to fully characterize the load state with sensors is not feasible. Instead, we identify components that have an unambiguous load state determined by their bearing, such as the bars in Figure 5 which are under uniaxial tension or compression. These load states can be captured with robust and cost-effective commercial-off-the-shelf technology. Existing sensor resources on the feller-pre-skidder vehicle are hydraulic cylinder pressure sensors providing load information, and displacement sensors providing information on position and orientation of the crane boom. All physical sensors have a corresponding virtual sensor in the EDT: Position sensors are represented in the multi-body dynamics simulation, and strain sensors can

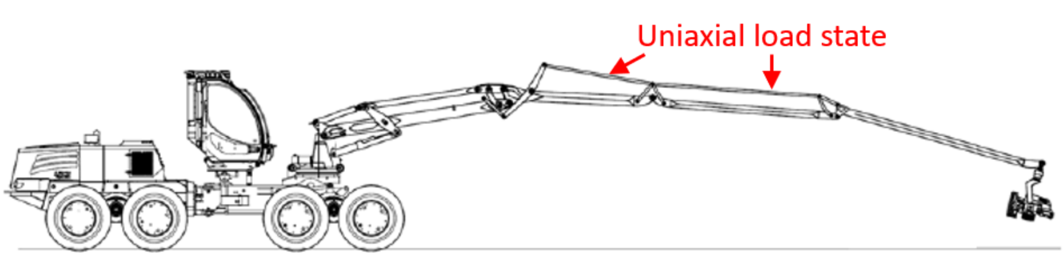

Figure 5. Load sensing at bars of uniaxial tension or compression is easy to implement with commercial-off-the-shelf technology.

be implemented by including elastic deformation into the EDT simulation framework, a feature that has been demonstrated in [8]. The EDT of the feller-pre-skidder vehicle will be used to generate training data for a multitude of use cases and their corresponding load spectra. A data-based analysis will identify load cases during the operational phase from the sensor network data, which enables continuous load monitoring and remaining structural life assessment.

Proposed demonstration experiment

We intend to test the proposed concept on a laboratory scale. With the demonstrator consisting of a simplified mechanism, one actuator, and two strain measurements, we cover all essential features of the lightweight crane boom, see Figure 6. We also supplement the physical hardware with an EDT for the demonstration mechanism to test the training data generation and validate data processing algorithms.

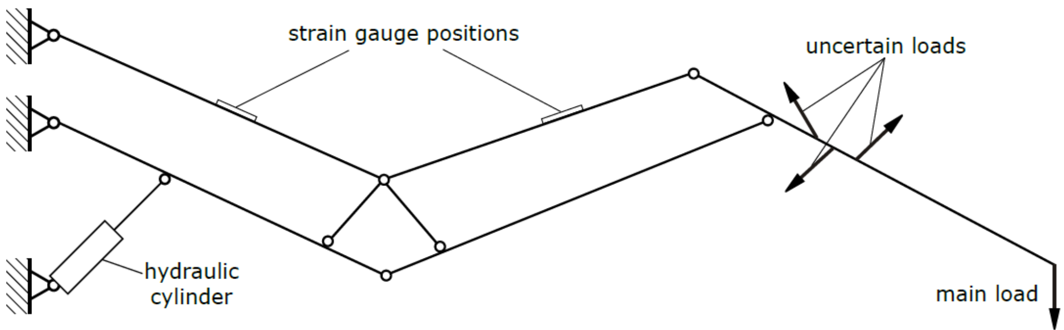

Figure 6. Proposed demonstrator for an experiment on laboratory scale.

CONCLUSION AND OUTLOOK

This paper presents our current work on the EDT of a novel feller-pre-skidder vehicle. We give an overview of the extensive use of EDT in virtual prototyping and the context of a driver assistance system. We suggest limiting the monitoring system of the lightweight boom to a load monitoring system, combining existing sensors with strain sensors for components under well-known load conditions, and using the EDT to generate training data. The upcoming work aims at demonstrating this concept on a laboratory scale.

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REFERENCES

1. Bundesministerium für Ernährung und Landwirtschaft. 2020. *Wissenschaftlicher Beirat Waldpolitik beim BMEL (Hrsg.) (2020): Eckpunkte der Wald-strategie 2050*. Stellungnahme.
2. zu Hohenlohe F, Kran, DE Pat 10 2023 104 654.3, 24.02.2023, pending
3. Schluse, M., Priggemeyer, M., Atorf, L., Rossmann, J. "Experimentable digital twins — streamlining simulation-based systems engineering for industry 4.0," In: IEEE Transactions on industrial informatics, 14(4), pp. 1722-1731, 2018
4. Schluse M, Rossmann J. "From simulation to experimentable digital twins: Simulation-based development and operation of complex technical systems," In: 2016 IEEE International Symposium on Systems Engineering (ISSE) 2016 Oct 3 (pp. 1- 6). IEEE. (2016)
5. Barat, V., Marchenkov, A., Kritskiy, D., 2021. "Structural Health Monitoring of Walking Dragline Excavator Using Acoustic Emission," *Applied Sciences*, 11(8), p.3420.
6. Misiewicz, Robert, Przemysław Moczko, and Bradley Boyce. "The use of thermoelastic stress analysis for stress distribution evaluation of an industrial equipment under regular operating conditions." Archives of Civil and Mechanical Engineering 22.3 (2022): 106.
7. Peng, Liang, et al. "Investigation of Structural Stress Monitoring System on Excavator under Impact Loads." *IOP Conference Series: Earth and Environmental Science*. Vol. 719. No. 3. IOP Publishing, 2021.
8. Krause, M., K.-U. Schröder, D. Kaufmann, T. Osterloh, J. Rossmann. "Coupling of rigid body dynamics with structural mechanics to include elastic deformations in a real-time capable holistic simulation for digital twins," in *32nd Annual European Simulation and Modelling Conference*, 2018. ESM 2018, pp. 77-81.