Onboard Adaptive Digital Twin for Commissioning Assistance Systems in Large-Scale Construction Machines with Cable-Suspended End-Effectors

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***Abstract*— Operators of Diaphragm Wall Hydraulic Grabs (DWHGs), a special type of large-scale construction machine with a freely oscillating cable-suspended end-effector, require assistance for smooth and economical machine control. The parameter setup or readjustment of assistance systems in such construction machines are time-consuming and manually done by skilled commissioning staff. This article presents a Digital Twin (DT) that provides the necessary information for assistance system configuration, thereby simplifying and accelerating the commissioning of the assistance system. The DT combines a PyBullet-based simulation consisting of simplified mechanical components with integrated hydraulic functional mockup units (FMUs) representing the hydraulic drivetrain. The simulation is systematically fitted to the physical DWHG behavior through parameter adaptation. A fidelity metric quantifies the alignment between simulation and real machine physics. The evaluation on a physical DWHG with an onboard industrial computer confirms the DT's real-time capability, enabling the extension of soft-sensing approaches towards combined sensing and actuating directly at the hydraulic level in future work.**

I. Motivation of Digital Twins and their Capabilities

The efficiency of building processes on construction sites depends mainly on the experience level of the construction workers, as many construction machines are still operated manually without intelligent assistance functions that compensate for machine operators' lack of experience and skills [1]. Studies have demonstrated that intelligent assistant functions enable a partially to fully automated or even autonomous operation, thereby improving construction speed, quality, and cost efficiency [2]. However, the commissioning of intelligent assistance functions is time-consuming, requires trained personnel and extensive trial-and-error runs to find a suitable parametrization for the underlying assistance to match the environmental conditions and machine's operating point. Significant changes in operating conditions require a manual readjustment of the assistance, leading to additional time effort and machine downtime [3]. Digital Twins (DT) offer a promising solution to the commissioning challenge of assistance systems in construction machines as they allow to shift the extensive trial-and-error runs from the physical machinery to the virtual DT representation, thus saving time and costs.

In this article, the challenging process of assistance setup for construction machines is considered for Diaphragm Wall Hydraulic Grabs (DWHGs), used in special civil engineering to produce a type of deep holes, called diaphragm walls (cf. Fig. 1). DWHGs are large scale construction machines with a cable-suspended end-effector, for example a bucket, that must be inserted into a narrow diaphragm wall to pick up soil material, pulled out, and swiveled to the storage location. This process is repeated several times and suffers from a back and forth swinging end-effector, when turning the DWHG between diaphragm wall and storage location. To support the human operator in damping the end-effector's oscillation, assistance functions using position controllers offer a promising solution [4], provided that the position of the end-effector can be measured [5]. However, installing position sensors on the end-effector or at the cable is not feasible, as they would be destroyed during excavation. In prior work, this measurement challenge is solved by the authors whereby the pressure oscillations within the DWHG's hydraulic

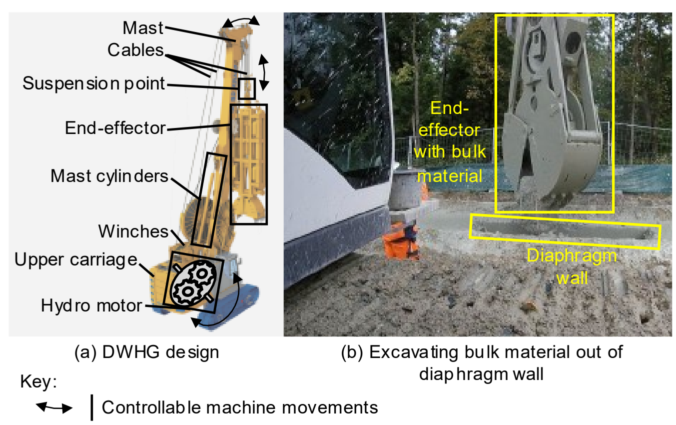

Fig. 1. (a) Schematic structure of a DWHG. (b) Excavation of soil from a diaphragm wall, from [6].

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actuators, which arise due to the end-effector's and cable's oscillations, are utilized to infer back to the end-effector's oscillation curve and position [6]. Consequently, a position controller with a hydraulic-based indirect measurement system can be retrofitted as assistance system's technical backbone for a DWHG and must be set up prior to application.

For the commissioning, the indirect measurement system must be parametrized with a ballpark estimation of the end-effector's and cable's oscillation frequencies and the position controller, that adjusts the hydraulic actuators, must be tuned for the desired DWHG movements.

According to current technology, the assistance commissioning is carried out by temporarily installing sensors on the machine, executing machine movements, analyzing the sensor data, and tuning the assistance through trial-and-error runs. To substitute for the time-consuming retrofitting of sensors and extensive trial-and-error runs with the physical DWHG, a DT can virtually provide the necessary information about machine behavior as well as a test environment for controller tuning. Therefore, a DT must be equipped with further **capabilities (C)** that a pure simulation is typically not provided with. According to the definition from Vogel-Heuser et al. [7], a DT in general must consist of application-specific components (**C1**), consider multiple scales such as size and time (**C2**), and be linked to the real world to enable continuous improvement (**C3**). Applying this DT definition to the DWHG use case results in three DWHG DT **features (F)**, presented below. The numbers F1-F3 indicate how the capabilities **C1-C3** must be realized for the DWHG use case.

First, the end-effector's oscillation is calculated from the pressure oscillation curves of the hydraulic actuators [6]. Thus, the DT must contain a simulation model with coupled hydraulic and mechanic components of the DWHG machine parts, which are modeled in sufficient detail so that oscillations from the mechanics (end-effector) can propagate into the hydraulics, as in reality (**F1: hydraulic mechanical coupling**). Second, DWHGs are equipped with industrial computers (IPCs), which have moderate computing power. The DT must be executed on these onboard IPCs, as cloud computing is not feasible due to the frequent lack of Industrial-Internet-of-Things (IIoT) infrastructure on construction sites (**F2a: onboard executability of coupled simulation**). The simulated end-effector oscillation behavior must be calculated in real-time, to enable a real-time estimation of the real end-effector position with high accuracy using the approach from prior work [6] (**F2b: real-time for end-effector oscillation simulation**). To explain in detail, typical DWHG operations lead to end-effector oscillations, which in turn induce pressure oscillations in the hydraulic actuators. The end-effector oscillation frequency, that is approximately equal to the oscillation frequency of the pressure signals within the hydraulic actuators, is required as an input to the pressure signal processing algorithm for inferring the real end-effector position of the physical machinery. Thus, the real-time capability must only be fulfilled by the mechanical part of the DT, so the simulation can be decoupled and the hydraulics neglected to save runtime. In this article, the stated real-time capability of the DT means that the simulation is executed at least as fast as the real-time behavior of the physical system. Third, the DT must adapt to new, changing DWHG types, operating points and environmental conditions to be applicable in DWHG operation (**F3: simulation-to-reality, sim-to-real, adaptation**).

The article's main contribution is a DT for a DWHG consisting of a simulation model with coupled hydraulic and mechanical submodels that can be executed onboard standard industrial computers under real-time constraints and dynamically adapt to the behavior of the physical (real) DWHG machine to simplify and accelerate the commissioning of DWHG's assistance systems.

The remainder of the article is structures as follows. Based on the related work (Section II), a DT for DWHGs is designed (Section III) and evaluated on an industrial physical DWHG (Section IV). Future work on the development of the DT is discussed in Section V.

II. Related Work On Digital Twins For Modeling Construction Machine Dynamics

In the related work analyzed, DTs of DWHGs are lacking the built-in features F1-F3 to cover the challenges C1-C3 (cf. Section I). To the best of the authors' knowledge, DWHGs in general have so far been rarely addressed in the research beyond the author group, which contributed an approach for DWHGs' end-effector trajectory planning using a simplified analytical model with parameter variations to reflect changing environmental conditions, but lacks the integration of real machine and hydraulic data to improve the model (F1: hydraulic mechanical coupling, F3: sim-to-real adaptation) [8]. Thus, in the following, first DT concepts for cranes, which are somewhat similar in structure and load oscillations to DWHGs, are analyzed.

Most of the crane DT concepts from related work take the real-time aspects of DTs (F2b: real-time for end-effector oscillation simulation) into account, even though concrete runtime benchmarks are not provided. Nevertheless, in contrast to the onboard-DT demand for DWHGs (F2a: onboard executability of coupled simulation), IIoT architectures on construction sites function as backbone for collecting real data from physical machines and running complex simulations on powerful hardware, as presented by Hussain et al. [9] (tower crane), Gao et al. [10] (overhead crane), or Li et al. [11] for crane systems which, however, consist of mechanical components without simulated hydraulic drive trains (lack of F1: hydraulic mechanical coupling). Huang et al. [12] used web platforms, which are less restrictive than IIoT, to run their detailed DT simulations of a crane girder, using the simulation software Ansys, which is not primarily intended for execution on onboard machine control systems (lack of F2a: onboard executability of coupled simulation). All DT concepts mentioned above rely on real data from the physical machine, which is a prerequisite to align the DT with real machine behavior (F3: sim-to-real adaptation). To synchronize a real-time capable dynamic simulation with the operating machinery (mobile log crane), Kurvinen et al. [13] focused on processing machine data using observer techniques, like Kalman filters, to correct deviations of real machine data and simulation. Even though a detailed simulation incorporating both mechanical and hydraulic components is employed and subsequently corrected, the approach lacks a runtime analysis of the onboard machine controllers (lack of F2b: real-time for end-effector oscillation simulation). Furthermore, it does not provide a systematic strategy for adapting the simulation parameters such that the model accurately captures the real machine behavior a priori, without requiring post hoc correction. To accelerate DT's simulation and make them computationally more efficient, surrogate modeling was proposed by Fu et al. [14] for an excavator, which has a completely other machine structure comparing to a DWHG or crane. They replace the simulation with an approximate model created from real machine behavior, which in general fits the demands of F2a (onboard executability of coupled simulation), F2b (real-time for end-effector oscillation simulation) and F3 (sim-to-real adaptation); nevertheless, the hydraulic drive train is not considered (lack of F1: hydraulic mechanical coupling), so it is unclear whether surrogate modeling techniques can accurately represent complex nonlinearities in hydraulics.

Furthermore, literature is analyzed on realization (simulation software) and adapting simulations (sim-to-real adaptation, F3) under consideration of real data from the corresponding physical machine that may be relevant for one of the features F1-F3, but without claiming to have created a DT according to the definition from Vogel-Heuser et al. [7].

For the design and implementation of simulation (F1: hydraulic mechanical coupling, F2a: onboard executability of coupled simulation, F2b: real-time for end-effector oscillation simulation), especially in control engineering, commercial software, such as MATLAB/Simulink is common, as exemplarily demonstrated by Makarov et al. [15] for a crane ship model. Such tools facilitate rapid model development due to their extensive pre-existing libraries. However, this convenience comes at the expense of computational efficiency, making them often unsuitable for simulation execution under strict real-time constraints on onboard machine computers. Thus, more lightweight simulation tools such as PyBullet, an open-source Python-based simulation platform, can mitigate the limitations of commercial systems in terms of runtime performance and system flexibility (relevant for F2b: real-time for end-effector oscillation simulation). Owing to its Python interface, PyBullet enables the straightforward implementation of simulation interfaces and facilitates deployment on open-source platforms. Consequently, it is widely used in reinforcement learning applications for mechanical system simulations; for example, Ishimatuka et al. [16] demonstrated the use of PyBullet for the simulation of an excavator. However, PyBullet does not natively support hydraulic modeling. Instead, it provides interfaces that allow coupling with external hydraulic and custom mechanical simulations. For example, it supports the integration of Functional Mock-up Units (FMUs), a standardized format for simulation model exchange. FMUs are widely used in the simulation domain to integrate subsystems, such as hydraulic components created in specialized hydraulic simulation software, into mechanical multibody simulations, as Ishida et al. [17] exemplarily demonstrated (relevant for F1: hydraulic mechanical coupling).

In the context of simulation adaptation approaches (F3: sim-to-real adaptation), simulation parameter estimation is discussed in the literature; Vaughan et al. [18] estimated in their model the frequency of crane load from further mechanical parameters, while Vyhlidal et al. [19] presented an algorithm to determine the amplitude of a crane's cable length. Both approaches enable the adaptation of individual simulation parameters. However, a comprehensive strategy to calibrate the entire simulation model to accurately reflect the real machine dynamics is still lacking (lack of F3: sim-to-real adaptation). To quantitatively assess the alignment between simulation and reality, fidelity metrics have been proposed, as outlined by Perfect et al. [20]. Yet, the integration of such metrics into a consistent and systematic parameter adaptation framework, as discussed by Mojallizadeh et al. [21] in their review on overhead crane modeling and control, for crane like simulations is still insufficient.

In conclusion, a comprehensive DT approach for DWHGs and comparable machineries that incorporates the features F1–F3 is lacking. Nevertheless, several promising directions can be derived; the combination of PyBullet with hydraulic FMUs represents a viable solution for implementing DWHG models. Furthermore, a systematic adaptation of simulation parameters based on the optimization of a defined fidelity metric appears to be a promising strategy for achieving accurate real-to-simulation alignment.

III. Digital Twin Design

A DWHG simulation including hydraulic mechanical coupling has been created (Section III.A), that can be executed onboard (Section III.B), and extended by a sim-to-real approach (Section III.C).

A. Simulation modeling

The simulation must include models of the DWHG's hydraulic drivetrain and mechanical components (F1: hydraulic mechanical coupling), with a strong emphasis on a lightweight,

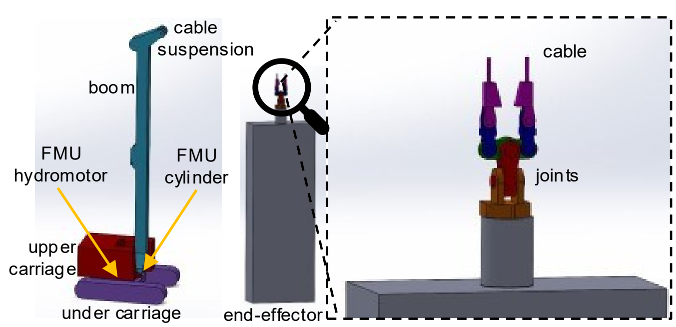

Fig. 2. Structure of the simulation consisting of 4 mechanical components and schematic representation of the FMU hydraulic interfaces (left). End-effector and joints for multidimensional end-effector oscillation (middle, right).

computationally efficient implementation (F2a: onboard executability of coupled simulation) that adequately represents the physical behavior of the machine. (F2b: real-time for end-effector oscillation simulation) requires only a mechanical simulation to calculate the end-effector oscillation frequency, which depends solely on the machine motion. Therefore, a high-level mechanical model without hydraulic subcomponents is sufficient. In contrast, (F2a: onboard executability of coupled simulation) requires a detailed hydraulic model to simulate how mechanical feedback propagates as pressure oscillations through the hydraulic actuators. For computational efficiency, a modular approach is adopted that separates mechanical and hydraulic subsystems and couples them only when necessary (use case of F2b: real-time for end-effector oscillation simulation).

To enable real-time simulation (F2b: real-time for end-effector oscillation simulation), the mechanical model (cf. compare sketch in Fig. 2, real DWHG in Fig. 1) consists of an under and upper carriage, which can be rotated by an optional hydraulic motor (additional hydraulic FMU), as well as a boom connected to the upper carriage via joints. The hydraulic mast cylinders between boom and upper carriage can also be optionally integrated using FMUs. At the boom, the end-effector is connected via cables and joints to enable oscillatory movement. All mechanical CAD elements consist of rudimentary geometric bodies to decrease computational efficiency, except for the cable and the cable joints (cf. Fig. 2, middle and right), whose dynamics are modeled in more detail to accurately represent realistic oscillation behavior. The mechanical models are exported from the CAD software in Unified Robot Description Format (URDF) to be easily reparametrized and integrated into the simulation. The hydraulic drivetrain, consisting of a hydraulic motor and mast cylinders (cf. Fig. 2, left), is modeled in detail in hydraulic simulation software by the component manufacturer, ensuring that it accurately represents the real hydraulic behavior. The simulation model was evaluated in collaboration with domain experts and validated through functional testing.

The hydraulic components are parameterized according to the real machine type and exported in FMUs.

B. *Simulation execution*

The DT is executed simultaneously to the DWHG trajectories applied from the operator on the physical machinery and mimics the real machine behavior virtually. PyBullet is used as core simulation tool according to the related work (Section II), as it is Python-based, lightweight, and compatible with Linux operating systems commonly used on onboard machinery and embedded systems. The simulation is structured in modular blocks with function calls (cf. UML sequence diagram in Fig. 3) and a fixed step size t to ensure deterministic communication. The core simulation consists of a library of mechanic models in URDF (Section III.A), a database containing mechanic model parameters (cf. Section III.C), an interface to the real machine data (DWHG's real trajectories), the PyBullet simulation tool, and hydraulic FMU models, which can be optionally included.

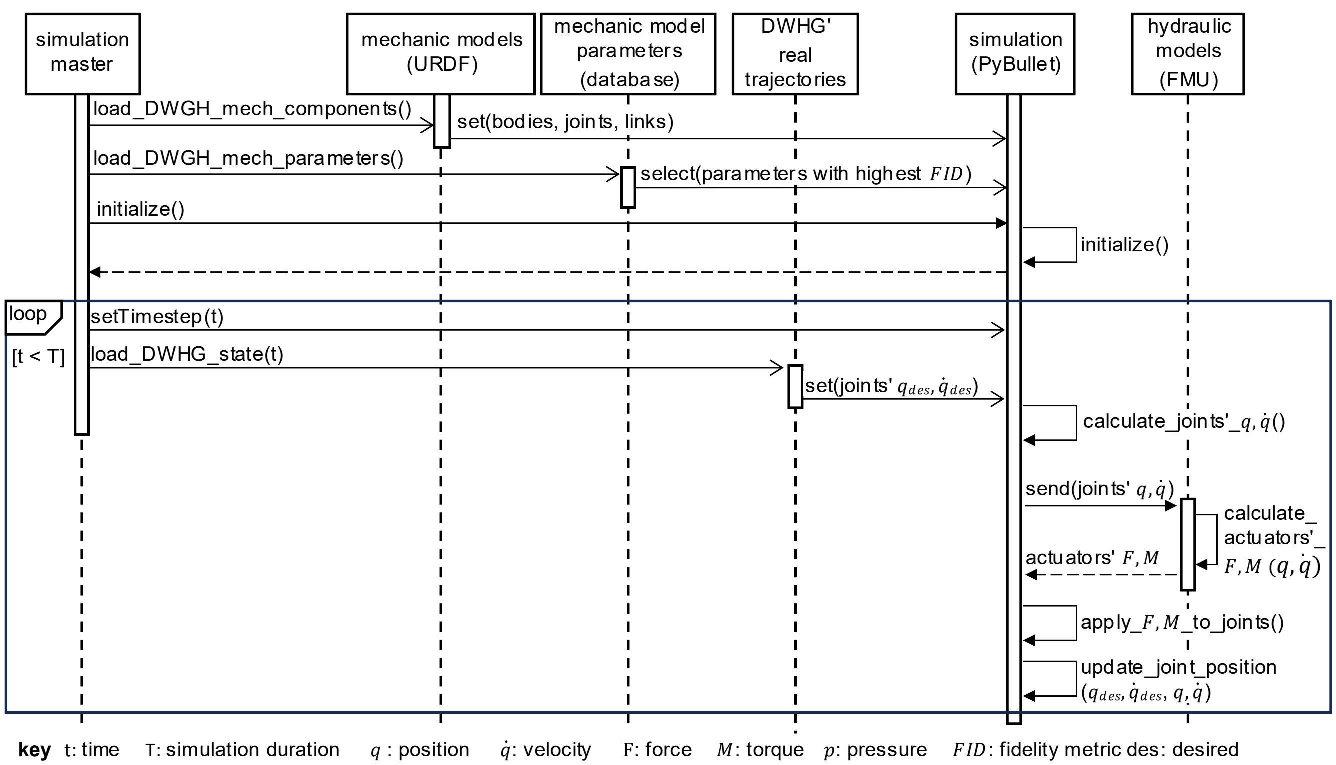

Fig. 3. Sequence diagram for executing modular simulation in a closed loop, with the DWHG's real-trajectory block serving as interface to physical DWHG.

The simulation master starts by loading and parameterizing the mechanical bodies with suitable model parameters (highest fidelity FID) (cf. Section III.C), joints and links and assembling them in PyBullet. In a loop, the simulation master schedules function calls and loads the DWHG states, represented by actual joint positions and velocities ($q_{des}, \dot{q}_{des}$). These are compared with the current simulation joint states, allowing PyBullet to calculate the updated simulation states (q , $\dot{q}$) and forward this information (flow variables) to the hydraulic FMUs. The hydraulic FMUs compute the forces (F) and torques (M) applied by the actuators (potential variables), which are then applied to the mechanics in the PyBullet simulation to update the joint states.

C. Simulation-to-real adaptation

To realize a sim-to-real adaptation, the simulation parameters of the highly simplified mechanical bodies, exported as URDFs, are systematically varied until a sufficient approximation of the physical DWHG behavior is achieved. A Design-of-Experiment (DOE) table is created with simulation parameters (factors) of the mechanical bodies, such as geometric dimensions, cable stiffness, or damping coefficients. For each parameter combination, a simulation run is executed in parallel.

To evaluate the alignment between simulation and physical machine behavior, oscillation frequencies from the hydraulics are analyzed. Typical DWHG operations induce end-effector oscillations, which generate pressure oscillations in the hydraulic actuators. As described in prior work [6], the hydraulic pressure oscillations consist of multiple superposed oscillatory components, which can be extracted using Fourier analysis. Therefore, a frequency-based approach is applied to assess simulation's fidelity, that indicates the degree of alignment between simulation and reality. For each experiment (simulation parameter combination), the fidelity is calculated using (1); for all oscillatory components of the superposed hydraulic pressure signal, the differences between real and simulated frequencies are computed and weighted by a factor. The weighting factor can be adjusted to prioritize highly important oscillation frequencies, such as the main frequencies of the end-effector's pendulum motion, while minimizing the influence of negligible frequency components.

$$FID = \sum_{i=1}^{n} P_i \cdot (1 - \Delta f_i)^2 \quad (1)$$

<u>with:</u>

FID: fidelity [-], 0: lowest fidelity, 1: highest fidelity
P_i: weighting factor [-] $\in$ [0,1]
Δf_i: normalized frequency deviation between simulated and reference frequency [-], defined such that $\Delta f_i \in [0,1]$
n: number of frequency components considered [-]

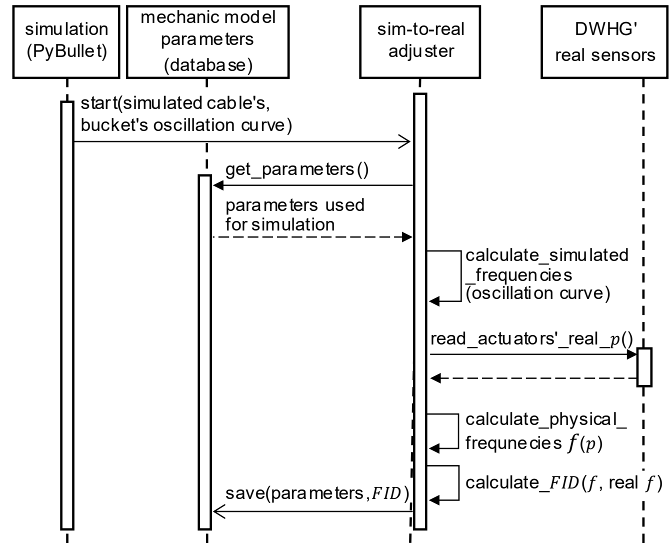

Fig. 4. Sequence diagram to realize sim-to-real adaptation.

Following this procedure in combination with the simulation environment (cf. Fig. 3), the parameter combination with the highest fidelity indicates the optimal simulation parametrization to mimic the physical DWHG (cf. UML sequence diagram in Fig. 4).

IV. Evaluation, Runtime Investigation and Application Scenario

First, the DOE table is created to systematically identify an optimal simulation parameterization that mimics real DWHG behavior, starting with initial ballpark estimates from technical DWHG datasheets. The simulation parameters are subsequently varied within a small range around these values, generating a full DOE table. Then, the DT is implemented and evaluated on a physical DWHG, that is operated to perform a short working movement, such as rotating the upper carriage. The end-effector comes into oscillation, which is measured using sensors at the physical machinery. For each experiment in the DOE table, the simulation is parameterized and executed with the same trajectory used for data collection on the physical machine, and the fidelity is calculated (cf. Section III). Following this procedure, a high fidelity of $FID \approx 0.92$ is achieved, which is notable under consideration that highly simplified mechanical models are used. The alignment between the high-fidelity simulation and the physical machine is further confirmed by simulation, hydraulic, and machine experts, validating the sim-to-real capability (F3: sim-to-real adaptation is fulfilled).

To investigate the runtime behavior of the simulation, a typical onboard IPC (SIMATIC IPC427E with an x86 architecture, i5-6442EQ CPU, and 16 GB RAM) is used and the real-time factor RTF is calculated using (2). It indicates how fast the simulation runs relative to real time; a value of 1 means the simulation proceeds in real time, values above 1 are slower than real time, and values below 1 are faster. The benchmarks are conducted without graphical simulation rendering for reasons of comparability.

$$RTF = \frac{T_{simulated}}{T_{real}} \quad , with\ T\colon total\ time\ [s] \qquad (2)$$

To evaluate (F2b: real-time capability of the mechanical part without hydraulics), the simulation is executed without the hydraulic FMU modules and achieves $RTF \approx 0.35$, indicating real-time performance. With additional FMU hydraulic blocks, an $RTF \approx 0.46$ is obtained for the hydromotor only, and $RTF \approx 35.05$ for the combined mast cylinder and hydromotor FMUs. The simulation with the hydromotor runs in real-time, whereas the full simulation does not, although it can still be executed onboard the IPC (F2a: onboard executability of coupled simulation is fulfilled). (F1: hydraulic mechanical coupling) is fulfilled, as runtime measurements demonstrate that the hydraulic blocks can be functionally activated and deactivated.

The full DT (with mechanics and hydraulics, $RTF \approx 35.05$) is only required for tuning position controllers, which is required once per construction site, as the position controllers, like PID, are robust enough. In the following, a short PID example, acting directly on hydraulic level is demonstrated using the DT simulation. This application example serves to evaluate the functional capabilities of the DT, while the synthesis of an optimal controller is not within the scope of this work. Therefore, a simple PID position controller for damping and end-effector position control is designed using the DT. According to [6], the mechanical end-effector position is inferred from hydraulic pressure oscillations, and the hydraulic actuators are controlled simultaneously. Thus, the hydraulic actuators function for both sensing and actuating. Within the whole simulation (including the FMU hydromotor and the FMU mast cylinder), PID parameter tuning is performed to design the assistance system. The position control of the mechanical end-effector can be fully realized on hydraulic level (cf. Fig. 5); the amplitude of the end-effector oscillation in tangential direction (orange line) and the amplitude of the pressure oscillation within the FMU hydromotor (blue line) both decrease, which is aligned with partial evaluation of this control, enabled by the DT, on the physical DWHG machinery. Additional functional tests with a physical DWHG indicate that the oscillation decay is significantly faster under active control compared to the natural damping behavior of the uncontrolled system, and further controller optimization in future work will significantly reduce this time.

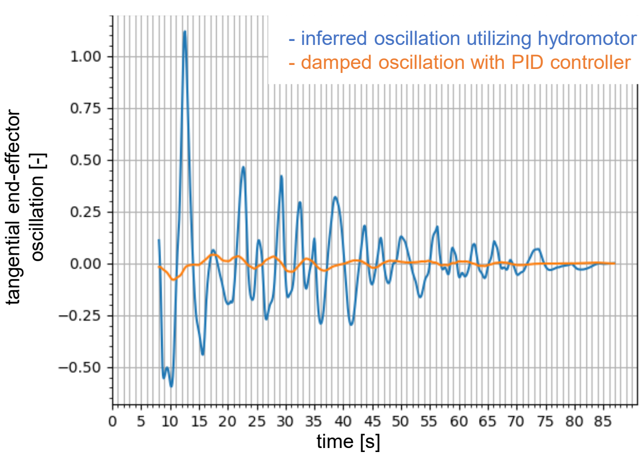

Fig. 5. Application example of damping assistance by sensing and actuating on hydraulic level. Due to confidentiality constraints, quantitative values for the tangential end-effector oscillations are not disclosed.

V. Summary and Outlook to Future Work

Operators of Diaphragm Wall Hydraulic Grabs (DWHGs), a special type of large-scale construction machine with a freely oscillating cable-suspended end-effector, require assistance for smooth and economical control. The setup and readjustment of such assistance systems are time-consuming and require well-trained commissioning personnel; the DWHG must be temporarily equipped with sensors to collect machine data in large experimental runs to tune the assistance. To address this commissioning challenge, a Digital Twin (DT) is proposed that replaces the manual assistance system setup by virtually providing the required information for assistance configuration. It simplifies and accelerates the overall commissioning process and enables automatic assistance tuning during DWHG operation. The proposed DT comprises three key features F1-F3. A PyBullet simulation model of mechanical components with an interface to simulation modules of the hydraulic drivetrain (feature F1: hydraulic mechanical coupling) can automatically adapt to real DWHG behavior (F3: sim-to-real adaptation) and model the full DWHG dynamics onboard on an IPC (F2a: onboard executability of coupled simulation) under real-time constraints (F2b: real-time for end-effector oscillation simulation).The alignment between the DT and the real DWHG is quantified using a proposed fidelity metric. The DT evaluation on an IPC and a physical DWHG demonstrates that real-time requirements are fulfilled and that the hydraulic drivetrain is modeled with sufficient accuracy. The modelled hydraulic drivetrain is capable of reproducing the intended functional behavior, which was validated in collaboration with domain experts. This enables previously developed soft-sensing approaches [6] to be extended towards combined sensing and actuating directly at the hydraulic level, allowing the hydraulic actuators to function simultaneously as soft-sensors and actuators.

Future work will conduct comprehensive controller validation in complex working cycles. In addition, a graphical user interface (GUI) will be developed under real-time constraints to support operators with visual simulation feedback. For this purpose, existing GUI rendering benchmarks for mobile machines from prior work [22] will be assessed to enhance the DT with graphical output capabilities.

Furthermore, oscillation damping and position control will be investigated in more detail to further analyze the prototypical hydraulic-level control structure presented and tested demonstratively in this work. The results obtained in this paper will be validated through extensive practical testing on construction sites using a simple PID controller, with the aim of identifying a suitable control approach capable of directly regulating based on hydraulic pressure oscillations. To this end, control signals as well as controller stability will be examined. In addition, the usability during commissioning using the proposed DT approach will be investigated with multiple human operators in order to quantify the cost savings achieved through virtual commissioning compared to the conventional trial-and-error procedure on the physical DWHG machine.

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