Digital Twin and Virtual Reality: A Co-simulation Environment for an Educational Hydraulic Workstation

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***Abstract*—Hydraulic system comprehension forms the pillar ofnumerous engineering fields; however, its academic assimilation remains intricate. Addressing this, our research introduces a digital twin-enabled virtual hydraulic workstation simulator developed in Automation Studio™. This simulator mirrorsa tangible hydraulic workstation, including its multifaceted components, to enhance the pedagogical paradigm of hydraulic education. We ensure the symbiosis of theoretical understanding and practical application by meticulously modeling 3D hydraulic components and executing analogous simulations. Our key findings spotlight the utility of time-dependent system behavior graphs in bolstering educational insights. The paper underscores the significance of digital twin solutions in university programs, mainly when physical resources are scarce, reinforcing educational technology's potential to facilitate studentengagement in technically dense arenas.**

***Index Terms*—Digital twin, hydraulic equipment, modeling andsimulation, experimental laboratory**

I. Introduction

Hydraulic systems, underpinned by fluid power mechanisms primarily driven by oil hydraulics, form the linchpin of numerous pivotal applications across various engineering sectors. Their remarkable significance manifests in civil engineering through water resource management, aerospace with precise aircraft actuation, marine systems for adept steering, and robotics for exact actuation. Further, it extends to agricultural machinery, mining ventures, biomedical apparatuses, environmental modeling, and state-of-the-art automotive systems. These systems have not only revolutionized equipment handling through precision control and torque multiplication but have also consistently showcased performance excellence in a multitude of industries. Their widespread adoption, from everyday machinery to the intricacies of aerospace operations, isa testament to their versatility and impeccable efficiency, cementing their foundational stature in driving the essenceof modern engineering innovations. However, despite theirunparalleled capability to generate substantial torques in compact spaces, they currently grapple with an impendingchallenge. In the burgeoning era of Industry 4.0, where digital technologies are swiftly advancing, the inherent worth of hydraulic systems is at peril, particularly when viewedthrough the prism of next-gen engineers and technologists.

Enter the Digital Twin paradigm: a transformative approach that stands poised to rejuvenate the realm of hydraulics. An intricate digital facsimile of a hydraulic system can be constructed using tools like Automation Studio™. This simulates physical operations in real-time and enhances the educational dimension by providing an interactive bridge between abstract hydraulic principles and their practical manifestations.

In an educational context, especially in universities where resource constraints might limit the availability of extensive hydraulic setups, the Digital Twin methodology presents aparadigm shift. Through this lens, students can dive deep into the mechanics of hydraulics without being physically present, thereby circumventing logistical and cost barriers. Such an approach can crucially retain the interest of a digitally-native student body, ensuring that the allure of hydraulics is maintained in a digital age.

Simultaneously, as the wave of Industry 4.0 swells, the convergence of the digital and physical spheres has become pivotal. The Digital Twin epitomizes this convergence. Withinthe academic domain, it has the potential to redefine traditional experimental laboratories, blending the advantages of virtual labs – scalability, safety, and universal accessibility – with the tangible, hands-on experience of remote labs. This synergistic fusion allows an experiential learning experience that is both immersive and secure.

As the boundaries of traditional education expand in response to evolving digital paradigms, the role of the Digital Twin becomes even more central. It symbolizes the future of versatile, dynamic, and inclusive academic methodologies. This transformative journey ensures that the essence of laboratory practices is preserved whilst making them more adaptable and resonant with the digital age.

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The manuscript is structured as follows: In Section 2, ”Related work”, a review of relevant literature is conducted, highlighting seminal contributions in the field. Section 3, ”Materials and methods”, comprehensively examines the hardware components, specifically the didactic hydraulic workstation, and introduces the computational framework, Automation Studio™. The ensuing ”Results and Discussion” section elucidates the intricacies of the digital twin for the hydraulic workstation, emphasizing distinct modeling characteristics and application nuances. The ”Conclusions” section encapsulates the principal outcomes and implications.

II. Related work

Digital Twin (DT) technology has been extensively reviewed, showcasing its transformative potential across diverse sectors, including engineering. [1] This technology, serving as a virtual mirror of physical entities, facilitates real-time data collection, validation, and simulation of its real-world counterpart. The review paper [2] highlights DT’s pivotal role in data-driven decision-making, system monitoring, and product lifecycle management while addressing the challenges inherent in its broad-scale adoption in engineering contexts.

Amidst the challenges posed by the COVID-19 pandemic to traditional experimental laboratories, especially with the shift to online learning modalities, another research advocated deploying Digital Twin technology as a viable recourse [3]. They emphasized that a DT-based laboratory proffers a digital or virtual counterpart of a physical system interconnected via the internet. This symbiotic linkage between the physical system and its virtual doppelganger retains the tangible interaction, concurrently amplifying the laboratory’s flexibility[4], [5].

In [6], challenges in fluid power education, such as outdated trainers and the increasing demand for online learning, have been addressed by developing a modern hydraulic trainer paired with its digital twin. This trainer integrates modernelectro-hydraulic components and sensors and is designed to offer a range of lab experiences, from basic actuator control to complex multi-actuator setups. Complementing this, a virtual trainer, developed using Unity 3D, mirrors the physical one, replicating the tangible lab experience, including common student errors and operational sounds. This virtual approach has been introduced as a promising solution for hands-on experiences in distance learning contexts.

In the extant literature, approaches towards the representation of digital twins in the context of hydraulic applications still need to be explored. While prominent hydraulic equipment manufacturers possess high-level modeling software to showcase applications from a marketing standpoint, these examples are conspicuously absent due to inherent modeling complexities in low-level modeling software, such as Automation Studio™ by Famic Technology. The approach delineated in our study is distinctively novel, offering a systemic perspective on developing a hydraulic workstation. Utilizing the 3D editor workshop within Automation Studio™, this workstation can be configured to illustrate various applications, thereby highlighting diverse operational scenarios. This methodology underscores the potential and versatility of integrating digital twins within hydraulic applications, bridging a notable gap in the current body of research.

Fig. 1: The didactic hydraulic workstation

III. Materials and methods

A. Hardware – didactic hydraulic workstation

The Tech-Con Hydraulic workstation, depicted in Figure 1, epitomizes a robust synergy between academic and industrial expertise. Through a dedicated sponsorship tailored for the Laboratory of Hydraulic and Pneumatic Drives, the university engaged in a fruitful collaboration with an eminent figure in the automation equipment arena. Even though the didacticworkstation of Eaton Hydraulics influenced its preliminary design, it underwent refined alterations to dovetail with the specificities of our laboratory environment. Designed withthe pedagogical environment in mind, it comfortably allows two students to work together, fostering a collaborative and immersive learning experience.

At its core, the workstation’s Fluid Direction Control is unparalleled. It boasts a drawer distributor encompassing four paths and three positions. Further enhancing its direction control capabilities, the workstation features a bi-positional solenoid valve that normally remains open and a non-return valve. Control over fluid flow rate is bestowed through a dedicated flow control valve.

Ensuring impeccable Pressure Regulation, the Tech-Con Hydraulic workstation is equipped with a sophisticated suite of valves. This includes a pressure-reducing valve for precise pressure adjustments. A sequence pressure and counterbalance valve supplement this, ensuring optimal pressure regulation across diverse hydraulic applications.

The workstation's Actuation Mechanism is its pride. Two double-acting hydraulic cylinders play a pivotal role. Cylinder2 is distinctively designed, housing an adjustable proximity sensor. In contrast, Cylinder 1 stands out with its unique springload, simulating a realistic piston advancement under load. Beyond these, the workstation accommodates a bidirectional hydraulic motor, emphasizing its diverse actuation capabilities.For real-time Pressure Monitoring, the workstation is adorned with two pressure indicators. While one remains affixed to the system's gallery, the other showcases remarkable flexibility, allowing users to mount it at any chosen point in the circuit. This ensures comprehensive pressure monitoring across the hydraulic setup.

The workstation's Electrical Control is streamlined through an ON/OFF switch, which could control the solenoid valve. The centrifugal pump, characterized by its potential to amplifypressure to 150 bar, is judiciously regulated. Given the academic context of its operation, a pressure valve is employedto cap the working pressure at a safer threshold of 50 bar.This meticulous approach prioritizes safety and aligns withthe typical requirements of a university laboratory setup. The power unit's electric motor, synchronized with a tri-phasic frequency converter, offers the added nuance of adjusting the hydraulic pump's rotational speed.

The components chosen reflect real-world engineering challenges and resonate with those predominantly encountered in modern hydraulic landscapes. Connected through flexible hoses and foolproof couplers, they pave the way for constructing an extensive range of hydraulic circuit configurations, mirroring practical applications.

B. Software Component: Automation Studio™

In the development presented in this paper, the Automation Studio 6.3 Educational Edition was instrumental in designing, simulating, and analyzing the hydraulic systems under study. Boasting an expansive Hydraulic Library, this software ensurescompliance with ISO 1219-1 and 1219-2 standards, offering users an exhaustive collection of fluid power components, fromthe basic such as pumps and motors to intricate measurement instruments and valves. Designed to cater to both the novice and the expert, the software comes equipped with built-in configurators, prominently featuring the Fluid Power Valve Spool Designer, allowing for the creation of virtually any valvespool position. Upon schematic completion, the true prowess of Automation Studio™ reveals itself, enabling real-time simulation. Animated schematics allow users to measure, in real-time, various parameters, enriching the analysis. This dynamic platform is enhanced by innovative troubleshooting tools, allowing users to simulate potential hydraulic failures and their subsequent effects. Automation Studio™ collaborateswith leading fluid power component manufacturers to further bolster its capability. This partnership ensures that users can integrate manufacturer-preconfigured components, bolstering the authenticity of their simulations. The software bridgesto Electrotechnical and PLC domains, not limiting itself to hydraulic systems, fostering a comprehensive environment for system analysis [7].

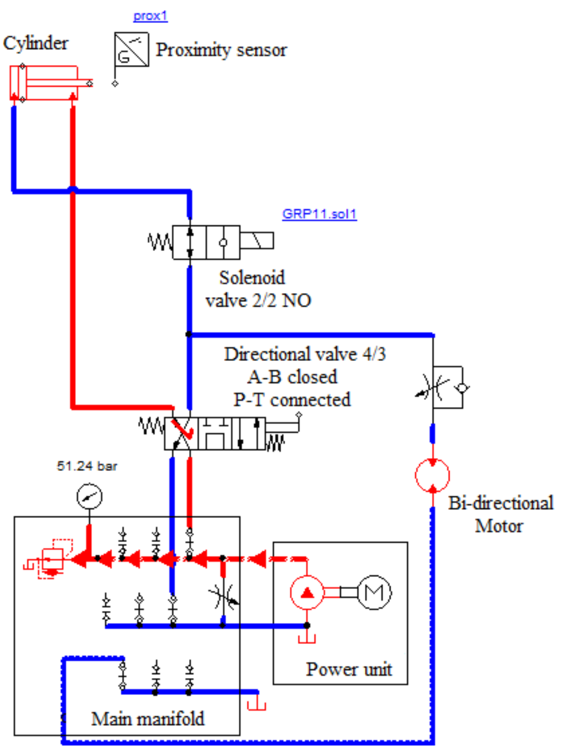

Fig. 2: Electro-Hydraulic Control Circuit Implementation

The hydraulic circuit design was executed in Automation Studio™, leveraging the extensive components available in the EATON library. EATON, a renowned hydraulic component manufacturer, provides a wide array of preconfigured elements within the software. These components cater to standard design necessities; however, specific and unique requirements were identified during the design phase. Automation Studio™, with its inherent flexibility, facilitates the creation of non-standard hydraulic equipment by adapting predefined components. This adaptability is essential for modifying components to meet specific design prerequisites.

Utilizing components from the EATON library streamlined the design and enhanced the simulation process. With the intrinsic simulation parameters of these components, thedesign's efficiency and accuracy were markedly improved.Consequently, the final design closely mirrored the anticipatedreal-world performance and behavior of the hydraulic system.In this research, the embodiment of the hydraulic system under investigation is vividly presented in Figure 2. Thisschematic offers a snapshot of an electro-hydraulic controlsystem. The schematic precisely captures the position control of the cylinder, facilitated by the proximity switch. This control element ensures that the cylinder halts movement onceit reaches a specific point. Simultaneously, the flow control valve depicted in the system plays a pivotal role in regulatingthe motor's speed, with the orifice size being the determining factor for this speed modulation.

This study aims to transition the hydraulic schematic in Figure 2 into a dynamic digital twin, realized in a three-dimensional model using the facilities offered byAutomation Studio's 3D workshop. This digital twin isnot merely envisioned as a representation of the hydraulicstand. Instead, it serves as a bridge, seamlessly connectingthe theoretical understanding of hydraulics with its tangible real-world application. Through this approach, a detailed and immersive simulation is facilitated. The shift from a static, two-dimensional representation to a vividly animated digital counterpart encapsulates this research's central ethos and aspiration. In adopting this approach, the constraints imposed by the physical hydraulic stand, which can accommodate a maximum of two students simultaneously, are effectively circumvented. Integrating this into a virtual application allows students to engage with the digital twin on their computer independently. This democratizes access and enables students to prepare and gain preliminary experience ina virtual environment. Such preparation is paramount as, while digital tools offer invaluable insights and practice, the hands-on, tactile experience at the actual hydraulic stand truly consolidates a student's understanding and skills in the realm of hydraulics.

In the field of hydraulic system simulations, Automation Studio's 3D editor elevates the concept of a virtual system to an advanced level, enhancing it by providing more seamless access to analysis based on the construction and simulation of the virtual environment. This editor facilitates the effortless creation of 3D parts and enables the import of 3D file formats, such as .STEP and .stl from other applications.

Capitalizing on this sophisticated feature of Automation Studio™, the digital twin's construction embarked on a sequential process, and the results are presented in Figure 3: The AL frame of the stand was crafted using fundamental geometric shapes, augmented with depth and realism through specific 3D effects found within the Visibility submenu of the Layout menu - Figure 3(a).

Subsequently, the Reservoir-Pump-Motor assembly was constructed. This was initiated with the tank's development, followed by articulation of the three-phase motor, positioned to the right, and the centrifugal pump on the left, as delineated in section Figure 3(b).

The following phase included two bidirectional hydraulic cylinders, with one endowed with a spring mechanism to emulate the effects of an external load - Figure 3(c).

Diverse valves were then integrated, encapsulating a normally open bi-positional solenoid, a directional check valve, a flow control, a pressure reduction valve, a sequential pressure valve, and a counterbalance valve - Figure 3(d). A spool distributor featuring a four-way, three-position design was also embedded, supplemented with an operative handle sourced from the HMI and Control Panels library. Concurrently, the main manifold for the hydraulic system's gallery was established, as discerned in - Figure 3(e).

Culminating the design, a bidirectional hydraulic motor wasplaced predominantly in the top - Figure 3(f), flanked by the ON/OFF switch, a pressure gauge, a proximity sensor, and theprimary command panel.

After the design phase for individual equipment pieces, emphasis was laid on the assembly of these components. Sucha meticulous step was indispensable to ensure the digital twin'salignment with the actual equipment housed in the laboratory. Central to this endeavor was creating connectors between the various circuit elements. These connectors manifest as hoses, each equipped with quick-coupling valves in alignment with the hydraulic blueprint presented in Figure 2. A pivotal phase involved connecting the integrated motor-pump-reservoirassembly to the system manifold, then to the pressure-reducingvalve, the spool distributor, the cylinder ports, the directional valve, and the bi-directional motor.

While the representation of the stand encompasses all real-world components, only a subset of these componentsis integral to the circuit under investigation in this paper.Components not implicated in the active circuitry have been rendered in shades of grey to enhance clarity and direct focus. This visual distinction serves a dual purpose: it accentuates theoperational components, which retain their foundational color while offering a holistic overview of the stand's entirety. To achieve a cohesive and realistic representation of the hydraulic system in action, 3D animations were judiciously deployed. These animations were vital in simulating both the extension and retraction of the cylinders, as well as the activation ofthe proximity sensor. Moreover, animations were integrated within the connectors, visually illustrating the flow directionof the hydraulic fluid. Components transitioning from dormantto operational were also subject to animation to provide a more immersive understanding.

The synchronization between these animations and the actual circuit was accomplished using internal variables embedded within each component's menu. Complementing this, two electrical control circuits were designed for the control panel and the spool distributor's flow direction toggle, respectively, along with a control circuit for the solenoid valve. Notably significant is the connection between the HMI panel and the motor within the circuit, governed bythe start/stop circuit, responsible for initiating or halting the stand's operation – Figure 4.

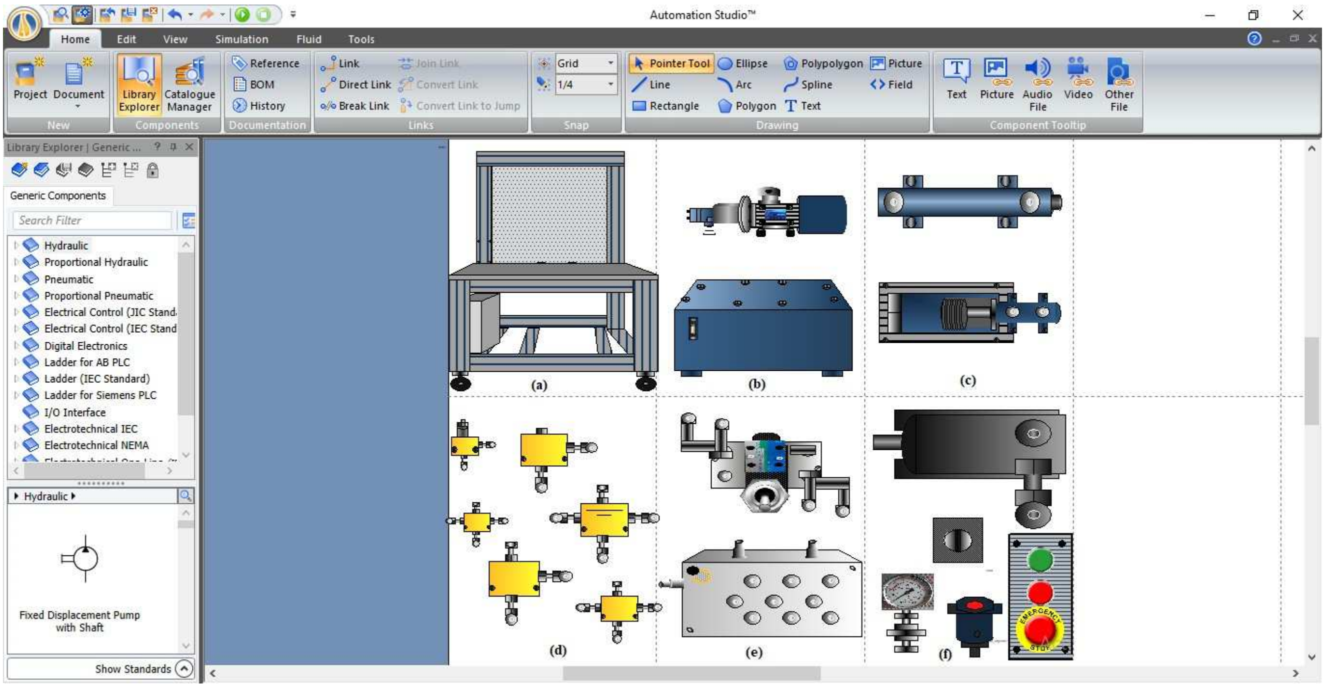

Fig. 3: Process of digital twin construction for the equipment from the hydraulic workstation in Automation Studio™

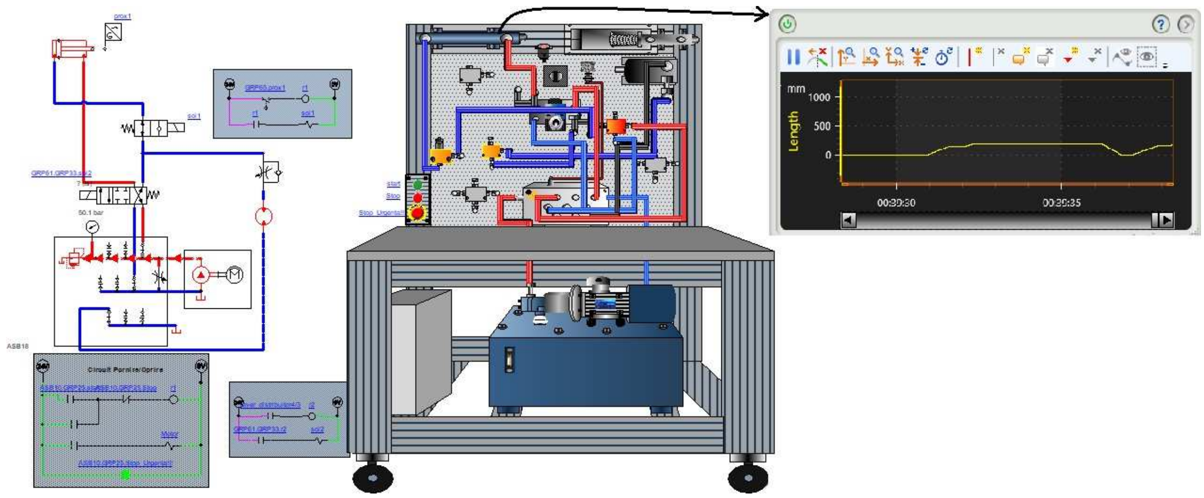

Fig. 4: Hydraulic workstation's digital twin in operation

IV. RESULTS AND DISCUSSION

The 'Simulation' menu facilitates the designed circuits' simulation. This menu grants access to various options, most notably, the 'Step by Step' progression and the 'Slow Motion' feature, optimized for enhanced visualization of the application in motion. The 'Measuring' section monitors and analyzes individual components' behavior during simulation closely. Here, one can graphically plot and observe the changes transpiring during the simulation process. Another vital subsection of this menu is the 'Troubleshooting', which offers a comprehensive set of tools such as an Oscilloscope, Multimeter, Hydraulic Tester, Pressure Gauge, Thermometer, and editing tools to ensure precision in measurements.

The simulation focused on a circuit whose primary actuationmechanism was a single bi-directional hydraulic cylinder, and its secondary component was a bi-directional hydraulic motor – depicted in Figure 4. The simulation sequence was inaugurated by activating the three valves within the system manifold, mirroring the real-world action of rotating the main valve on the system gallery casing. The subsequent step involved assessing the functionality of the command panel. This panel was designed employing elements from the HMI library. These were connected to the hydraulic circuit's motor via an electrical schematic responsible for receiving anddispatching electrical signals through a solenoid and associatedcoils. The functionality of the ’Start’ button was tested, which,

upon activation, instantaneously actuates the motor. The latter subsequently drives the pump, instigating the flow of hydraulicfluid in the circuit. Post this, the ’Stop’ button was assessed, leading to the immediate cessation of the tri-phase motor.

The ’Emergency Stop’ is a paramount feature in any systemdue to its role in abrupt equipment halting during technical anomalies. Effective reactivation can only be accomplished after the identification and rectification of the underlying defect, coupled with the release of this button. Importantly, irrespective of the ’Start’ button being pressed, the electric circuit design inhibits the motor’s activation as long as the emergency button remains engaged.

To glean a spectrum of measurements, spanning from pressure, positioning to acceleration and velocity, the specialised tools offered by Automation Studio can be employed. Figure 4 exemplifies this utility. Specifically, this figure showcases the plotting of the piston’s position with its displacement time, subsequently facilitating the derivation of its evolution graph. This graph delineates the trajectory of the piston over time, highlighting its dynamic behavior during the simulation.

Utilizing the advanced capabilities of Automation Studio augments the precision of observational data, forging a robust correlation between tangible operations and their digital counterparts. The data extracted from these tools is quintessential, ensuring that real-time actions in the physical realm seamlessly mirror the digital twin, eliminating operational discrepancies.

One salient instance is the hydraulic cylinder’s behavior, where the hydraulic oil’s flow rate is paramount. Discrepanciesbetween the digital model and the real-world apparatus hint at potential deviations in the parameters set or the operational timeline. Addressing such discrepancies is pivotal to enhancing the fidelity of the digital twin’s portrayal.

A suitable remedy to reconcile these deviations is the recalibration of the hydraulic oil flow rate, considering the integral relationship between this metric and the cylinder’s actuation speed. A closer emulation of the real-world system’skinetics becomes attainable by judiciously adjusting this parameter within the digital twin’s parameters. This iterative process ensures enhanced synchronization, harmonizing the digital representation with its tangible counterpart.

Furthermore, a standout feature intrinsic to the real-world hydraulic system is the capability to fine-tune the motor’s rotational speed using a static frequency inverter. This adaptability facilitates tailored control of the motor’s dynamics, aligning them with specific operational needs. This real-world sophistication is mirrored with precision within the digital twin. Embedded in its model is a feature that allows forthe specification of the rotational speed (in rpm) of the drive motor for the centrifugal pump. Such integration emphasizes the digital twin’s comprehensive nature, capturing even the most intricate operational nuances.

V. CONCLUSIONS

The significance of a digital twin in educational settings becomes increasingly apparent. The accuracy with which the digital twin replicates the real-world hydraulic workstation determines its precision and educational allure. By closely mirroring real-world functionalities, the digital twin offers students a robust, immersive learning platform that connects theoretical knowledge with practical applications.

The modular nature of this co-simulation environment showcases its adaptability and scalability. This allows for the easy integration and activation of additional hydraulic and electrical components, enhancing its comprehensive educational potential. Such flexibility ensures the digital twin can be effortlessly expanded as the hydraulic domain evolves and grows. It is a future-proof and invaluable tool for in-depth understanding and exploration of complex hydraulic systems.

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