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Next Generation Hardware-in-the-Loop Simulation Enables Advanced Testing of Offshore Hydraulic Systems

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Abstract

With the increased spotlight from global classification societies on the requirements for Hardware-in-the-Loop (HIL) testing, the objective of this paper is to prove how, with the use of advanced testing of control systems in a virtual environment, HIL simulations can be successfully incorporated into operations to reduce overall rig downtime as well as reduce commissioning times and product delivery timelines – eliminating the need to conduct costly and timely full-scale equipment testing.

Initially, results from modeling and simulating the existing offshore hydraulic hoisting system in a virtual environment are compared with reference data measured on a real plant; resulting in a high level of observable data and accuracy. Secondly, the process utilizes Process Field Bus (Profibus) components simulation; establishing the communication platform between the controller and virtual machine on which the dynamic simulator of the modeled system runs. Finally, real-time simulations are performed; including, but not limited to, interaction with a virtual model of the hoisting system via a programmable logic controller (PLC).

Among the major results and recordable observations of the project, is establishment of a complete HIL testing simulator. Drilling machinery can be modeled with object-oriented physical modeling software and its operation can be controlled by using real controls hardware and software. Additionally, accurate real-time simulation of offshore equipment is executed on readily available computer hardware. Resulting in a data-driven solution that generates both cost- and time-savings during both delivery and commissioning of drilling packages ultimately reducing operational downtime.

The methodology presented within this paper is a significant step change in the field of HIL testing of offshore hydraulic-mechanical systems; as primarily models of drilling equipment used typically so far are relatively simple and easily simulated on a conventional PC. However, the development of this next generation HIL testing offers comparatively increased solutions in both simulation fidelity and modeling efficiency. With the application, this next generation HIL simulation strategy provides for both the successful HIL testing of selected offshore machinery and can closely reproduce original field performance data.

Introduction

Commissioning time for offshore drilling equipment has always been a key concern for manufacturers within the industry. The companies strive to deliver quality results in an expected time. However, unforeseen events, poor planning or external factors might influence the target delivery time. It is especially critical for large size equipment, like a hydraulic hoisting system analyzed in the current work. Due to its size, testing its different functionalities is time consuming and costly. Therefore, there are usually strict time constraints on tuning the control algorithms before commissioning of the equipment. These operations have to be performed onsite, which makes a rig not operational for the time it takes to evaluate the control system. Hence, there is an increasing need for a tool which makes it possible to examine real controllers in a virtual simulation environment without the need to conduct onsite tests.

Modeling and simulation software becomes increasingly popular in the design of offshore drilling machinery. It mitigates the effort of design engineers allowing them to test and redesign various solutions in a virtual simulation environment, according to Pawlus et al. (2014a). In addition, virtual prototyping indirectly helps to reduce the number of offshore accidents due to the fact that the critical or malfunctioning components of the equipment can be identified early in the design stage. This is a strong argument which supports the effort of creating more realistic and reliable simulators of marine systems. Safety of the offshore personnel has always been one of the key concerns for equipment producers, according to Skalle et al. (2014). Chen et al. (2008) addressed that issue by pointing out that hardware-in-the-loop (HIL) testing is essential for marine structures and offshore equipment to reveal failure effects caused by software failures and design flaws. Hardware-in-the-loop (HIL) testing is a dynamic method of testing of the control system software, where the actual software is executed on its native hardware. The control system software running on a programmable logic controller (PLC) acts against the simulator which imitates the behavior of the actual equipment. Consequently, HIL aims not only to improve cost effectiveness, speed, and repeatability of simulation based engineering but also to improve safety of human operators working in offshore conditions.

Therefore, in the current work we present the results of HIL testing of a full-scale hydraulic hoisting system. The virtual model of the machine is created using a multi-domain modeling software. The complex model is further optimized for real-time (RT) performance by following the methods described by Pawlus et al. (2014b). Achieving RT performance of the simulated equipment is critical for successful evaluation of the developed control system in a virtual environment. A complete laboratory setup composed of commercially available components is applied to execute HIL tests and the workflow to assemble and connect the setup is explained. The results of the HIL simulation are benchmarked against the field data recorded during a regular operation of the real world hoisting system. A high level of accuracy is observed while at the same time the simulator does not violate the RT process execution requirement.

Description of the Hoisting System

Typically, a hoisting system analyzed in this paper is composed of a guiding construction inside of which there is moving a traveling block with sheaves, according to Zhang (2011). As stated by Bednarz and Teper (2012), hydraulic hoisting systems have been used in water exploratory drilling since the beginning of 1950s. They were introduced to the oil drilling industry much later, when the problems of manufacturing accuracy and leakproofness were solved for large size machinery handling high loads. Nowadays, still the most popular solution used worldwide for drilling applications is a well-known conventional drawworks based rig (DWBR). However, the importance of hydraulic hoisting systems is increasing in exploratory drilling, as well as in harsh environment and in ultra-deep water areas – see work done by Skjelbred (1997). The most critical factors that offer improvements as compared to traditional DWBRs are: hoisting and compensating system efficiency, lower weight and center of gravity, tubular and blowout preventer (BOP) handling, as well as safety and working environment.

Figure 1–The hydraulic hoisting system – MHWirth, (2015).

The hydraulic hoisting system considered in the current work is shown in Figure 1. According to Pawlus et al. (2014b), it is composed of hydraulic cylinders and a wire-rope mechanism that hoists / lowers the payload. The traveling yoke connects both cylinders and travels vertically in a guiding construction. The yoke supports the sheaves which run the hoisting wires from the wire equalizer assembly to the drilling machine. The traveling yoke is placed on rod end of the cylinders with one integrated guide trolley supporting each side. The cylinders are placed in line next to the guide rails, one on each side of the well center. These are plunger cylinders hence there is no possibility for air to accumulate under the cylinder piston and create undesired flexibility in the system. The cylinder clamps are fastened to the guide rail. The cylinder manifolds include valves for control and safety of the cylinders. In addition, the cylinder top is connected to a bleed valve which is responsible for letting out gas particles (de-aeration) from the hydraulic fluid. The central hydraulic power unit (HPU) supplies the hoisting system. Up to 12 pumps are driven by diesel engines or constant speed AC motors. By adjusting the speed and power of the hoisting system it is possible to save or distribute the energy for different drilling operations. The hydraulic fluid from the tank, depending on the type of technological operation, could be supplied to cylinders, drained back to the tank, flow in the oil and gas accumulators system or power another drilling machines. Operations realized by the hoisting system are controlled by an operator from an intelligent operator chair (IOC). Hoisting, lowering, passive / active compensation, landing of subsea equipment, etc. are among the major functions of the considered hydraulic hoisting system, according to Vatne and Norheim (1996).

An additional advantage of this machine is its ability to regenerate energy. It is achieved by storing the hydraulic energy in accumulators when the cylinders are being retracted. Additionally, accumulators could be charged by pumps. Another advantage is the decreased size and mass of the hoisting system. Since, the vertical loads resulting from the payload are transferred by the cylinders, the amount of structural elements above the drill floor (DF) level and steel constructions is reduced. This results in lower center of gravity and reduced space requirements, which in turn increases the variable deck load (VDL) capacity.

Mechanical and Hydraulic Systems Modeling

The mechanical and hydraulic model of the hoisting system is formulated analytically and implemented in a multi-body virtual modeling software. Details on model establishment are presented in the work of Pawlus et al. (2014b). The principal idea is to create two virtual models of the considered system. The first model is an accurate representation of the hydraulic connection diagrams. It is validated against full-scale measurements. However, because of the high level of complexity and computational demands it is not applicable in RT testing of control systems. Therefore, a simplified model that has only the major functionalities of the overall system is created. It produces equally accurate results as the high-fidelity model, while at the same time is capable of running in RT. The changes made to the complete model do not affect the reduced model performance in scenarios being considered, i.e. hoisting / lowering and active heave compensation (AHC). In the current work, the model optimized for real-time performance is used for testing the control system. The mechanical assembly to be controlled through the hydraulic actuation system is illustrated in Figure 2.

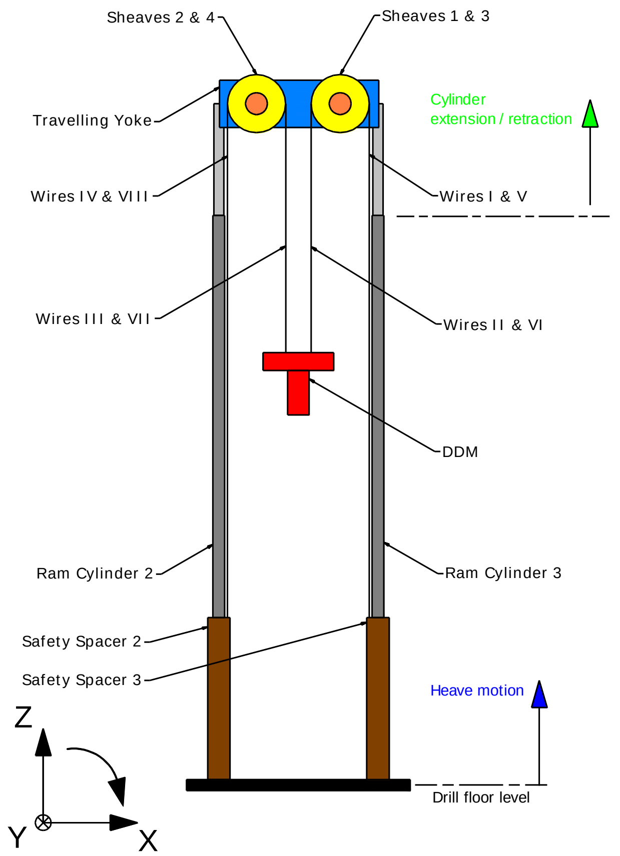

Figure 2–Schematic representation of the hoisting system – Pawlus et al. (2014b).

By comparing the simulation time with the elapsed, real world time it is possible to assess the RT performance of the simulator. If the total delay, defined as the difference between the simulation and elapsed times, remains constant, the simulated model is capable of running in RT. Of course, there occurs an initial delay when the simulation starts but as long as it does not grow over time, the RT performance is unaffected. In the case of an increasing total delay, the computational power required by the simulator is too high which prevents the system from running in RT. Contrary to that, if the total delay decreases it indicates that the simulation is running ahead of the real world time. This is achieved when a variable step-size solver is applied and the simulated system does not require significant computational power. This situation is also unwanted from the perspective of the RT testing of control systems, as it does not guarantee the execution of the simulation at a fixed rate.

Control System Architecture

Hoisting / Lowering Mode

For controlling the analyzed system during hoisting / lowering a feedback cylinder position proportional control and feedforward cylinder velocity proportional control are used. They regulate the flow delivered by HPU in order for the derrick drilling machine (DDM) to follow the reference trajectory. For such a type of control there exists a steady-state error during ramp up and ramp down of signals, however in a steady-state this error disappears due to the action of feedforward velocity controller. The schematics of the proposed control system are shown in Figure 3. The feedback position gain P_{FB} and feedforward velocity gain P_{FFW} are selected during the tuning process to provide for satisfactory system response.

Active Heave Compensation Mode

The AHC mode compensates for the forces the ocean heave applies to the rig, i.e. the compensator tries to obtain small force variations / movement in the hook when ocean heave is moving the rig. A passive compensator (compressibility of the nitrogen with no extra energy added) will only damp the load motion. However, the nitrogen is not able to compensate for friction without extra energy added. To add this extra energy, the possibility to control the accumulators' pistons is implemented. The heave motion of the platform is measured continuously by a motion reference unit (MRU). The control system uses this signal to position the accumulators' pistons to provide steady hook load. A feedback accumulator position proportional control and feedforward accumulator velocity proportional control are used to regulate the spool position of AHC control valves in order for the accumulators to follow the reference trajectory (to mitigate the effect of heave motion) and for the DDM to move as little as possible. The schematics of such a control system are shown in Figure 4. The feedback position gain $P_{FB:AHC}$ and feedforward velocity gain $P_{FFW:AHC}$ are selected during the tuning process. Accumulators' pistons are controlled individually in anti-phase with the rig heave.

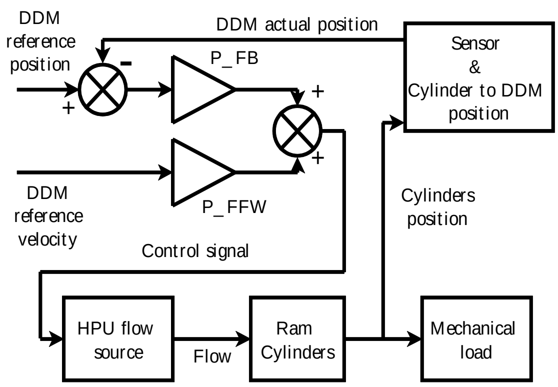

Figure 3–Concept of hoisting / lowering control.

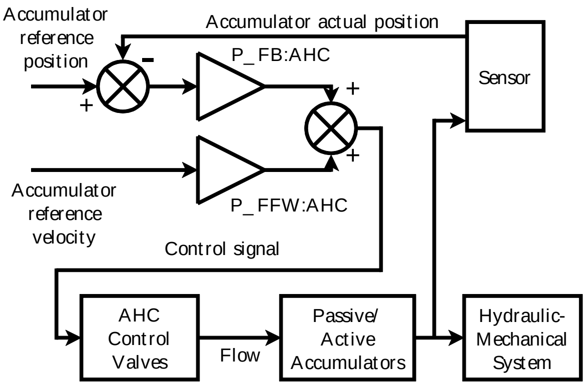

Figure 4–Concept of AHC control.

Hardware-in-the-Loop (HIL) Setup

Concept

The following hardware system is set up to execute HIL tests as illustrated in Figure 5:

1. Host PC – A computer which controls execution of the simulation model.
2. RT Target – A computer that is running the simulation model on a dedicated RT operating system.
3. Programming PC – A computer that emulates RT interactions of a human operator with the system.
4. Interface Device – A hardware interface which simulates Profibus devices.
5. Programmable Logic Controller (PLC) – A real world controller which is used to regulate operation of a simulated plant.

In addition, a multi-body modeling software is required, as it serves as a tool to create a dynamic model of a system and test its performance offline, without a need to connect it to any of the devices mentioned above. The host PC and programming PC might be integrated into one machine. The reason for splitting them up in the current work is to allow an access to all components that are located away from the human operator e.g. in a server room. Therefore, the programming PC works here as a terminal to allow remote operation of the setup.

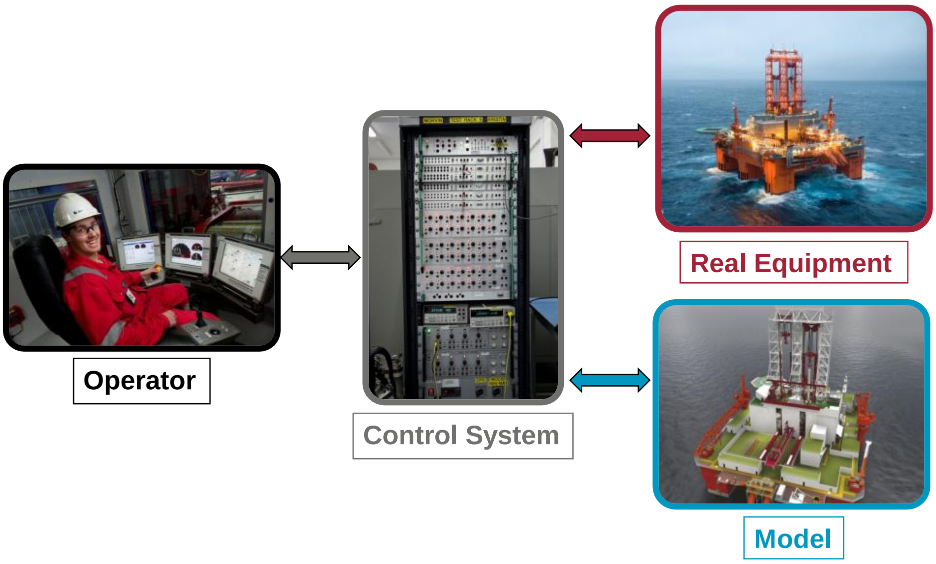

Figure 5–HIL simulation concept.

The constraint of RT execution of a simulation model has crucial importance for HIL tests. The real world controller is running with fixed cyclic interrupts, therefore, if one wants to simulate a plant which is connected to the controller, it should also keep RT capability. In order to achieve it, a real-time operating system (RTOS) is used in the current project to simulate the model. Furthermore, it is connected via the TCP/IP with the host PC, making it possible to develop and program algorithms on the host PC and deploy and execute them in RT on the RT target. Such a system is used first to verify RT performance of the models before connecting them to the remaining elements of the hardware setup, i.e. to the interface device and the PLC.

The interface module applied in the current work is a system for simulating field bus devices using Profibus DP / PA (Decentralized Peripherals / Process Automation) protocol and / or Profinet protocol. This tool supports simple inputs / outputs from Profibus slaves as well as dynamic simulation of user defined complex functions for end devices e.g. motors, valves. The behavior of such devices can be manipulated using integrated digital control logic modules. The interface module is mapping the controller outputs with the inputs of the model and vice versa. It is essential to associate each controller output with the corresponding signal in the model, which is a requirement for a complete HIL test. The simulator provides the functionalities for quick design and testing of automation projects during factory acceptance tests (FAT).

HIL Testing Implementation

The hardware setup illustrated in Figure 6 is established to realize the HIL concept shown in Figure 5. A simulation model is deployed on the RT target form the host PC through the TCP / IP connection. The host PC communicates with the interface module which exchanges data with the PLC via Profibus. The TCP / IP connection of the PLC is used to download hardware configuration and controller architecture from the programing PC. Finally, once the program executes on the RT target, the data is transferred back to the host PC, then through the interface device to the PLC, and back. This is the most critical path to be checked to ensure that communication delays do not affect the RT performance and results accuracy of the simulator.

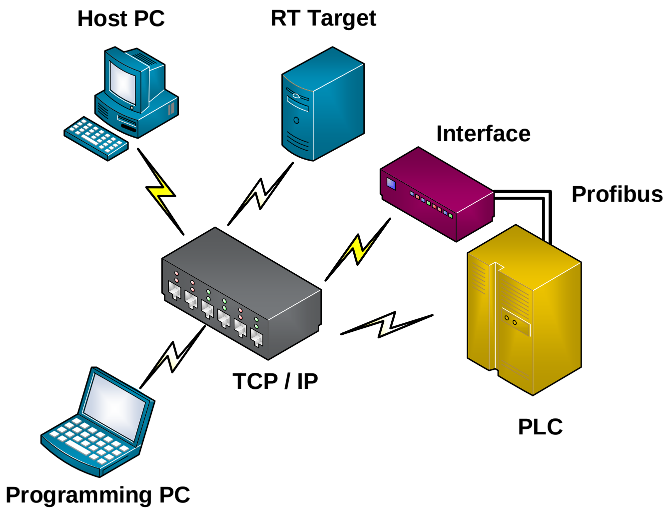

Figure 6–Hardware connections setup for the HIL simulator.

Control Loop

Figure 7 shows the data flow between particular components of the HIL control system. Set points generated by the human operator are transferred to the controller running on the real world PLC (the same which controls the full-scale machine) which in turn produces the appropriate signals to actuate the modeled system. Process variables which are measured in a virtual simulation environment on the RT Target are fed back to the real hardware controller to regulate operation of the machinery. In addition, the measured data could easily be displayed and monitored by an operator on the programming PC. The risk factor associated with such an implementation is related to the fact that the simulated model on the RT target is running at a lower sampling frequency (because of model complexity) than the minimum cyclic interrupt on the PLC. However, it is validated in the current work that this mismatch between step-sizes does not cause additional difficulties in the communication process nor simulation errors.

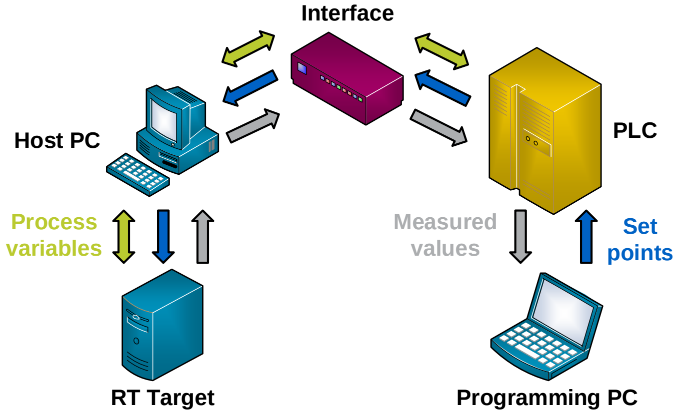

Figure 7–Control loop implemented for the HIL simulator.

Simulation Results

Field data acquisition is performed during a regular operation of the hoisting system. Real world position and pressure signals are measured during the AHC scenario. These profiles are applied to validate the virtual model of the hoisting system used in the HIL simulations. The same input signals are applied as set points to the simulator and the responses of the tested system are recorded and benchmarked with the full-scale data acquired on the rig to assess accuracy of the HIL test.

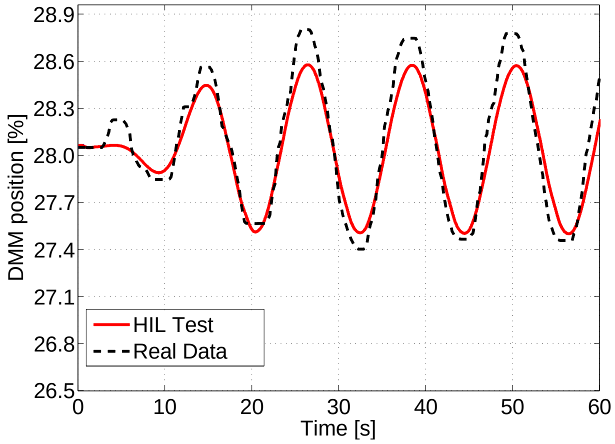

Figure 8–Comparative analysis of DDM position during AHC.

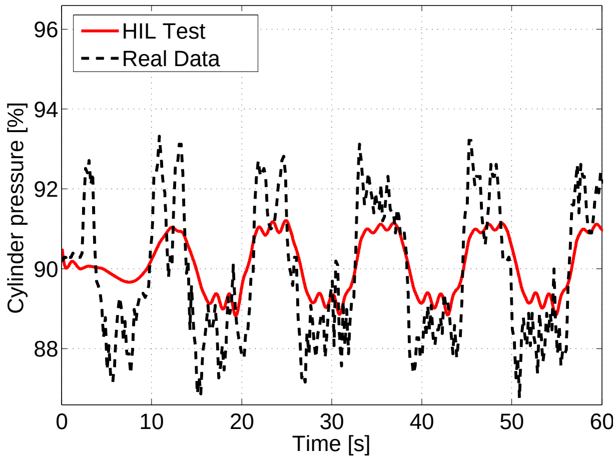

Figure 9–Comparative analysis of cylinder pressure during AHC.

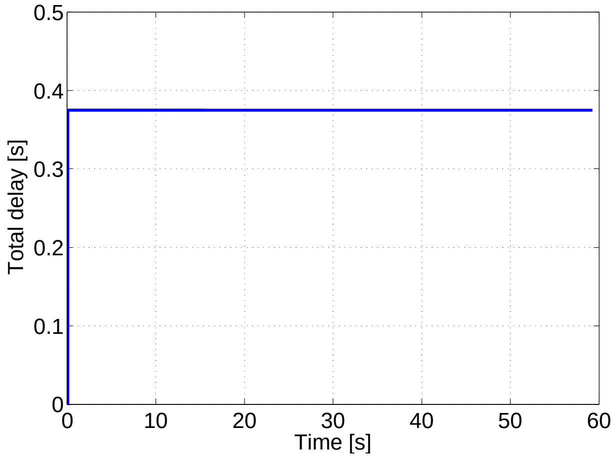

Figure 10 – Total delay for AHC simulation.

On the RT target a fixed step-size Runge-Kutta 4 (RK 4) solver is used with the step-size being equal to dt_{FIX} = 1E−3 s. In the trial and error method it was verified that step-sizes lower than dt_{FIX} = 1E−3 s do not yield a RT operation of the simulated model. The comparative analysis showing a detailed model validation and results accuracy when using a variable step-size backward differentiation formula (BDF) solver to simulate the model is presented in Pawlus et al. (2014b). Simulation results for AHC scenario during HIL testing are illustrated in Figure 8 and Figure 9. Both pressure and position profiles shown in this work are normalized with respect to the load induced pressure for empty hook (no payload) p_l and maximum travel of DDM $d_{\max}$.

Based on the obtained results, it is concluded that RK 4 fixed step-size solver is sufficient for our application. It successfully provides for both accurate results and RT performance of the simulation. It is observed that transferring process variables through the PLC to use them in the control loop does not cause instability of the simulation. In addition, the results of the HIL test prove that the behavior of the virtual hoisting system corresponds well to the behavior of the real machine. Differences in cylinder pressure are related to the fact that no friction in the hydraulic cylinders have been considered. For the analyzed scenario the total delay does not increase and maintains a constant value throughout the simulation, as illustrated in Figure 10. The initial delay is caused by the short time span which exists between starting the simulation and initializing all simulation states. A constant value of the total delay is an indicator that the simulator is running in real-time.

Conclusions

This paper presents the results of HIL testing of a hydraulic hoisting system. A complete HIL simulator has been established and confirmed to work successfully for models optimized for RT performance. Not only the results of the simulator closely reproduce reference, real world measurements recorded during a regular machine operation, but also the simulator is conveniently controlled in real-time by a human operator. The results of the current work can be successfully applied to evaluate and examine real control systems in a virtual simulation environment, reducing the need to conduct costly on-site tests on a full scale equipment, time spent by control systems engineers offshore, as well as shorten commissioning time and product delivery period. In addition, all of these factors help to increase safety of personnel working offshore and reduce risk of injury or fatal accidents. On top of that, a realistic opportunity to generate cost and time savings during delivery and commissioning of drilling packages is created. Ultimately, the results of the current work directly correspond to an increasing attention which classification societies pay to HIL testing, e.g. Det Norske Veritas (2011).

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