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A Methodology for Real-Time HiL Validation of Hydraulic-Press Controllers Based on Novel Modeling Techniques

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ABSTRACT Industrial machines commissioning consumes a great amount of man-hours, due to control designers lack of knowledge about the final controller gains before they start working with it. Virtual commissioning has been postulated as an optimal solution to deal with this lack of knowledge when the Real-Time simulation of the digital models reproduces an identical behaviour as the industrial machines they represent. Cyber-Physical Systems (CPSs) offer new opportunities in this field, however, in the case of industrial machines, acquiring this level of accuracy requires to slow down the simulation. On this paper, novel modelling techniques for industrial CPSs have been presented. They are introduced to help in the evolution from conventional control design to a virtual commissioning process combining software and hardware capabilities. This methodology has been tested with a hydraulic-press model designed following manufacturer specifications, initially under a Software in the Loop (SiL) validation platform and, afterwards, in a Hardware in the Loop (HiL) validation platform. The control algorithms are designed in laboratory conditions harmless for the machine, embedding them later in the industrial environment without further modifications.

INDEX TERMS Electrohydraulics, hydraulic systems, real time systems, system-level design, virtual manufacturing.

I. INTRODUCTION

Commissioning, as the last stage in any industrial machine design phase, consumes a great amount of man-hours [1]. Despite being crucial in the overall process of building these machines, its extra charge reduces entrepreneurs attitude in investing and improving their controllers. This factor becomes exacerbated if it is taken into account that some controller modifications are done thousands of miles away from manufacturer's infrastructure. With such disadvantages, industrial machine controllers lack from regular improvements, consuming more project budget during the commissioning stage in order to improve system overall reliability [2], [3].

Recent improvements in software tools have opened the door to new possibilities in the field of model design, as well as, the introduction of new system integration platforms and advanced controller validation techniques, which decrement the cost and risk of commissioning [4]–[6]. Nonetheless, further integration and streamlining of the commissioning process is yet worth seeking, with the aim of reducing the error-prone and high computational cost models, closing the gap between simulations and real system operations [7], [8].

This novel techniques sight for more trustful models, reducing the breach between the simulated industrial machine and the response performed by the one installed on

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the manufacture. This leads to develop models capable of performing identical responses as the real machines, creating a Cyber-Physical System (CPS) of the industrial device [9]–[11]. When these models are simulated in Real-Time [12], [13], the response obtained with the real machine and the CPS is synchronized, enabling the virtual commissioning process. Nonetheless, due to the discrete response performed on the virtual environment, simulating complex physical properties, such as hydraulic non-linear equations, in fixed time demands high computational costs, which in some cases is unachievable. Even though there are tools to slow down model simulations, they require to sacrifice Real-Time performance, avoiding the possibility to export and embed the model into a hardware platform.

The limited data available for industrial components also affects the virtual component performance, as it increases the difficulty to reproduce industrial machine behaviour trustworthy in digital environment [14]–[16]. Acquiring a precise digital model of an industrial machine requires laboratory experiments to determine part of their physical properties, due to most of them are not directly obtainable, increasing the commissioning process cost and making even less appealing introducing these procedures in industrial environments.

These drawbacks justify the seek for a novelty in the field of model design for industrial machines. The new technique sights for CPSs with Real-Time performance modelled at the system engineering level and capable of enough fidelity for virtual commissioning [17]–[20]. It brings new benefits in the field of model design for industrial machines, as the set of equations defining the CPS are based on data-sheet information rather than complex physical properties. This assumption is possible due to an abstraction in the parameters and variables defining the machine behaviour, maintaining the ones relevant to accomplish a similar performance between the CPS and the real machine, decreasing the simulation time without loosing feasibility [21], [22].

With them, the industrial machine is designed following manufacturer specifications and tested under a Software in the Loop (SiL) platform [23]–[28], in order to validate the model behaviour. For instance, on this paper a hydraulic-press has been presented as the case of study. Afterwards, the model has been exported and embedded in a Real-Time simulation platform. It allows the engineer to test and verify the final control responses with exactly the same hardware that would be placed in the industrial machine, developing the virtual commissioning. The Hardware in the Loop (HiL) platform [29]–[31] validates in laboratory conditions and harmless for the machine the designed control algorithms, exporting them afterwards into the industrial environment without further modifications.

The improvements brought by these novel techniques and the virtual commissioning methodology are presented in the paper on Section II, clarifying the process followed from control design phase to virtual commissioning, through the analysis of a new library designed to generate CPSs of industrial components, implementing them under a SiL and HiL validation platforms. Afterwards, on Section III a hydraulic-press is modelled generating a virtual-twin prepared to test the capabilities and limitations of this novel methodology in both validation platforms. Finally, Section IV exposes the conclusions drawn from the paper.

II. METHODOLOGY FOR VIRTUAL COMMISSIONING

Virtual commissioning is reached following a design process which involves the initial creation of machine diagrams and it evolves into a validation stage under two platforms, one based on software technology and the other one on hardware technology [32]–[34]. This virtual process requires a digital model capable of performing identical responses in Real-Time as a real machine, that is to say, a Cyber-Physical System. Section II-A analyses the state of art of modelling techniques and introduces the novelties brought to that field in the paper. On Section II-B, the component modelling process is presented. On the last section (II-C), the HiL validation platform is sought to design the controllers and to compare deterministic communication protocols.

A. DESIGN TECHNIQUES

This paper presents a methodology to realize virtual commissioning based on a Hardware in the Loop validation platform, in which controllers are tested against a digital model of the system in a harmless environment. The models used in the simulation require to be executed in Real-Time in order to ensure the feasibility of the validation. This context contributes to search for new design techniques to reduce the simulation time without losing accuracy between the digital model and its real counterpart.

HiL validation platform connects real and virtual systems, as it is pointed in [35] and [36]. As these authors explain, systems share characteristics of both environments, being the task of the control designer to determine which components are going to be simulated in software and which ones in hardware environment. After this classification, they explain how Real-Time behaviour is achieved when virtual systems clocks are synchronized with real ones through a deterministic communication protocol.

Multiple authors support this classification and suggest different platforms to develop the Hardware in the Loop validation. For instance, the same Fennibay et al. in paper [37]; Moussaab et al., in [38]; Montana et al., in [39], and Ali et al., in [40]. Synchronizing these software and hardware platforms requires models capable of being simulated in Real-Time. On [41], Ersal et al. exposes the problem to achieve the balance between model accuracy and speed during simulations. It deals with this situation presenting multiple algorithms suitable to reduce the complexity of models until they become proper for control system simulation.

Chris et al. in paper [42] remark this idea, arguing how they need to acquire the balance between too detailed physic-based models with extensive simulation time and oversimplified systems. On this context, Cyber-Physical Systems seems a suitable solution as they are heterogeneous, hybrid, distributed and Real-Time systems. This procedure constructs useful models for simulations, as [43] and [44] expose. Both papers coincide in considering CPSs a wide open modelling technique, as they allow designing high level detailed models to lighter versions of them in pro of acquiring the Real-Time simulation.

They encapsulate the physical properties into components instead of a whole system, facilitating the task to design complex models. The Real-Time performance is acquired when the CPSs equations reach the convergence in fixed time, which depends on the integration method selected to solve them. For instance, in [45], Thomas et al. gather these components into a library designed by them to simulate Real-Time models of liquid cooling networks. Even though the existent libraries, as the one mentioned before, are capable of simulating models in Real-Time, they lack from this characteristic, when they are used to build up industrial machines models, due to their complex circuit.

Reproducing industrial machine behaviour in Real-Time requires high simulation times, due to the fact that these systems are complex models that combine equations from multiple physical properties. This factor makes difficult to connect the CPS to a controller, as they need low simulation times to ensure system stability.This synchronization between model and controller is reached when the physical properties slowing down the simulation are identified and simplified.

In the presented work, we improve the actual techniques to design CPSs introducing novel concepts which sought simplify models of industrial machines in order to reach the Real-Time performance. These concepts reduce the simulation time required to attain equation convergence without loosing precision between the response performed by the real system and the virtual one. The new characteristics introduced are the following ones:

- **Low Complexity:** It is sought to acquire a balance between the necessary parameters to describe the physical behaviour of the model and the ones that slow down the simulation. This new procedure requires the abstraction of low level details, going from integrating complex models at system design phase, rather than component design phase.
- **Data-sheet-level parameters:** Constructive details are hard to identify (in most cases, reverse engineering is required in order to measure them) and provide few information when characterizing component equations. The models are configurable by simple inspection of data-sheets, which allows their direct draft at the system design phase.
- **Data-sheet-level fidelity:** The physical behaviour of industrial machines is defined through data-sheets, so the new techniques sought to reflect this performance. In addition, reaching high levels of fidelity requires introducing complex mathematical expressions in the components equations that are not reflected on these manuals. The models perform identical responses as the ones obtained in the data-sheets, minimizing computation time without compromising the fidelity of the system.

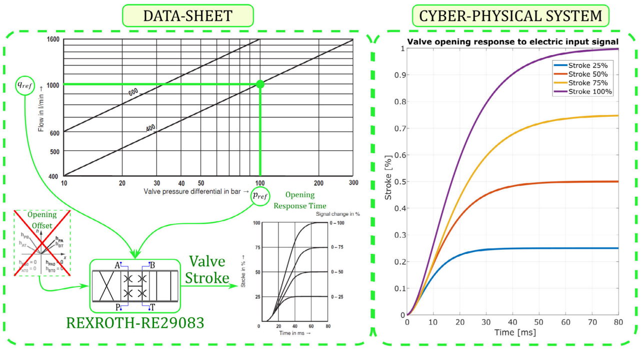


FIGURE 1. Parametrization of a proportional valve model with a novel technique based on information brought by data-sheets.

Taking into account these characteristics, a new library has been configured with models of industrial machines components, which are easily configurable with information extracted from data-sheets diagrams. Fig. 1 represents the procedure a user should use when parametrizing one of these components, in this case a proportional valve. The component parameters (reference flow rate and pressure) are extracted from data-sheet graphs, avoiding to obtain constructive parameters, such as the opening offset for each port. In these technical documents, the manufacturer ensures a opening response time which is represented on the small graphic at the right down corner in Data-Sheet representation on Fig. 1. When the model is simulated, the response acquired during the process is similar to the one specified by the manufacturer, ensuring the data-sheet fidelity of the novel modelling techniques introduced.

B. SIL IMPLEMENTATION

The library mentioned in II-A has been prepared to create CPSs of industrial machines, which requires to reproduce, in virtual environment, the physical properties defining these elements. Simscape^{TM}, one of MATLAB$^{®}$ toolboxes, offers a suitable platform to imitate this behaviour. This approach differs from Simulink$^{®}$ language because with it a network representation of the system is created instead of an equivalent mathematical model, in a designing process called Physical Network Approach. Each system is represented with standalone functional elements interacting and exchanging information between them through non-directional ports, wired following an analogue process as combining physical components. The limit of ports in a component is defined by the system, but each one has two variables associated, one called through (static in time) and the other one named as

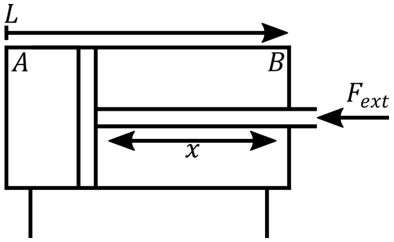


FIGURE 2. Schematic of a double acting cylinder.

across (time dependant). For example, in mechanical translational systems, force is the through variable and velocity the across, while in hydraulic systems, pressure acts as the through variable and flow rate as the across.

Each component designed with the new library presented on this paper must follow the statements previously commented on Section II-A, in addition to the novel design techniques. Even though a system is defined by variables, component inner attributes are also taking into account as constants to describe its behaviour. For instance, in the case of a double acting cylinder (Fig. 2), the flow rate through the chamber is defined by the following equations, variables (v) and constants (c):

$$q_A = A_A\dot{x} + (V_{d_A} + A_A x)\beta\dot{P}_A \tag{1a}$$

$$q_B = -A_B\dot{x} + (V_{d_B} + A_B(L - x))\beta\dot{P}_B \tag{1b}$$

$$m\ddot{x} = A_B P_B - A_A P_A - F_{ext} \tag{1c}$$

where:

TABLE 1. Equations, variables (v) and constants (c) defining a double acting cylinder.

q_A, q_B	is the flow rate through port A and port B, respectively (v)	$[m^3/s]$
P_A, P_B	is the pressure in chamber A and chamber B, respectively (v)	$[Pa]$
x	is the piston position (v)	$[m]$
L	is the actual position of the piston (c)	$[m]$
A_A, A_B	is the area of chamber A and chamber B, respectively (c)	$[m^2]$
V_{d_A}, V_{d_B}	is the dead volume of chamber A and chamber B, respectively (c)	$[m^3]$
β	is the compressibility factor of the fluid (c)	$[1/Pa]$
m	the lumped moving mass of the cylinder piston (c)	$[kg]$
F_{ext}	all external counteracting forces (v)	$[N]$

This modelling techniques has been adapted with the novelties explained in Section II-A to design industrial components. On this scenario, Fig. 1 shows a Cyber-Physical System of a proportional valve designed following this specifications. In this case, due to being a hydraulic component, the through variable is the pressure in the port and the across variable is the flow rate. The geometric parameters which describe the proportional valve model are extracted from data-sheet information:

$$q_{xy} = r_{xy} \cdot sign(P_x - P_y)\sqrt{|P_x - P_y|} \cdot \frac{q_{ref}}{\sqrt{P_{ref}}} \tag{2a}$$

where:

TABLE 2. Physical properties definition for hydraulic equations in proportional valve Cyber-Physical System.

q_{xy}	is the flow rate through port X to port Y	$[m^3/s]$
r_{xy}	is the flow ratio between port X and port Y	$[1]$
q_{ref}	is the reference for the valve flow rate	$[m^3/s]$
P_x	is the pressure at port X	$[Pa]$
P_y	is the pressure at port Y	$[Pa]$
ΔP_{ref}	is the reference differential pressure	$[Pa]$

The equation presented does not contain the opening dynamic of the valve (τ). In this case, the proportional valve changes its position infinitely fast, which is impossible in a real system. To solve this incongruence, the model is improved with an input/output relationship, where u represents the control signal (the input) and y_v the valve opening (the output):

$$\frac{\tau^2}{16}\ddot{y}_v + \frac{\tau}{2}\dot{y}_v + y_v = u \tag{2b}$$

The proportional valve is opened in a range between −1 and 0, when the signal is negative, and between 0 and 1, when the signal is positive. When the input signal is 0, the valve will remain closed. The oil flowing through the ports (q_p, q_t, q_a, q_b) depends on their volume (V_{port}), the pressure (P_p, P_t, P_a, P_b) and the bulk modulus (K):

$$q_p - q_{pa} - q_{pb} - q_{pt} = V_{port}\frac{\dot{P}_p}{K} \tag{2c}$$

$$q_t + q_{bt} + q_{at} + q_{pt} = V_{port}\frac{\dot{P}_t}{K} \tag{2d}$$

$$q_a + q_{pa} - q_{at} - q_{ab} = V_{port}\frac{\dot{P}_a}{K} \tag{2e}$$

$$q_b - q_{bt} + q_{pb} + q_{ab} = V_{port}\frac{\dot{P}_b}{K} \tag{2f}$$

On Fig. 1 it is appreciated the identical response between the virtual model and the real system. Despite some hydraulic physical properties have been simplified, the assumptions made earlier are accomplished; the model is configured with data-sheet parameters and the response has enough accuracy to be considered data-sheet fidelity. In order to prove the low complexity of the component, a deeper analysis comparing our model against its Simscape^{TM} variant is presented.

In Simscape^{TM} a proportional valve requires to be defined on the constructive parameters, for instance, the flow discharge coefficient, the valve opening offsets and the maximum opening. They are obtainable only through laboratory experiments, as they are not usually available in data-sheet information, which makes harder for industrial workers to design a virtual model of their machine.

The flow path of a Valve orifice opening depends on the offset selected by the user, which introduces four new

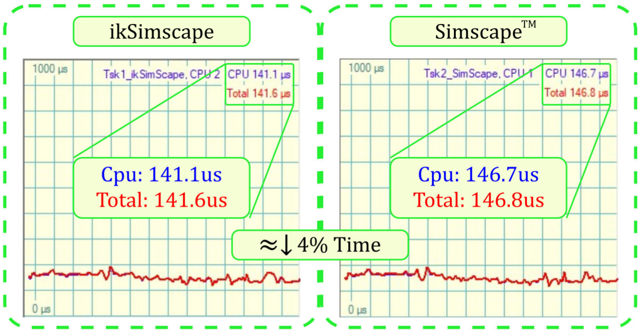


FIGURE 3. **Comparison between the time required to achieve equation convergence in a Simscape proportional valve against its counterpart designed with the library presented on this paper.**

equations to compute each flow path separately, depending on the opening offset:

$$h_{xy} = r_{xy0} \pm x \tag{3a}$$

where:

TABLE 3. **Definition of orifice opening equations in Simscape^{TM} proportional valve model.**

h_{xy}	is the orifice opening of the X-Y flow paths	$[m]$
h_{xy0}	is the orifice opening offsets of the X-Y flow paths	$[m]$
x	is the spool displacement relative to what in the zero-offset case is a fully closed valve	$[m]$

In addition, this equations must be solved in each iteration to obtain the opening area for each port in the proportional valve, which is defined in the following equations:

$$A_{xy} = \frac{A_{xy,Max}}{h_{xy,Max}} h_{xy} + A_{Leak} \tag{3b}$$

where:

TABLE 4. **Definition of opening area equations in Simscape^{TM} proportional valve model.**

A_{xy}	is the opening area of the ports X-Y	$[m^2]$
A_{Leak}	is the leakage area	$[m^2]$
h_{xy}	is the orifice opening of the X-Y flow paths	$[m]$

Parametrizing a component with Simscape^{TM} requires a deeper analysis, an effort avoided in ***ikSimscape***, as we have called this novel library for industrial components. In addition, introducing these dynamics slows down the simulation, as the test carried out in Fig. 3 shows. On them, we have designed two identical hydraulic circuits (Fig. 6) and in one we have substituted the proportional valve from ikSimscape to its Simscape^{TM} counterpart. Both circuits are going to be simulated under similar conditions: an integration method based on Backward Euler algorithms and a fixed step size of two milliseconds. As it is appreciated, our model requires less time (approximately 4%) to attain equation convergence.

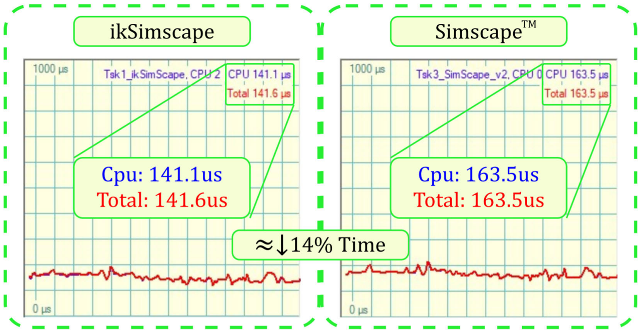


FIGURE 4. **Comparison between the time required to achieve equation convergence in a Simscape proportional valve against its counterpart designed with the library presented on this paper.**

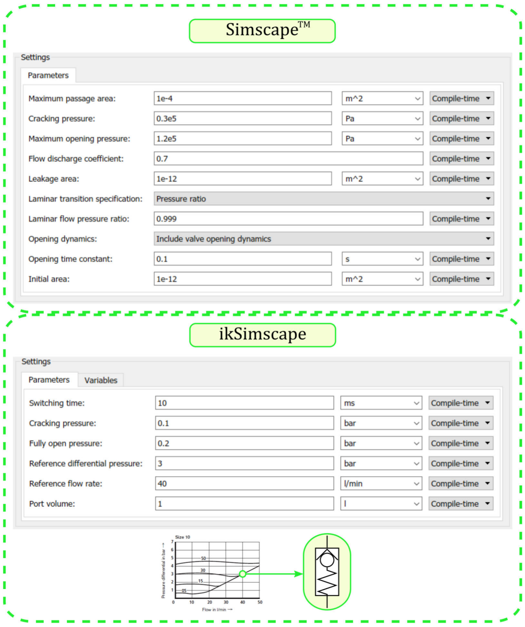
The bridge between both simulation times is increased when more Simscape^{TM} components are added to the hydraulic circuit. In Fig. 4, we have also substitute the pipelines for Simscape^{TM} versions, which leads to a separation of near 14%. This experiment proves the assumptions made on Section II-A, showing how Simscape^{TM} components attain equation convergence in more time than its ikSimscape counterparts.

This factor becomes exacerbated in industrial machines, as they are compound of more than fifty components. Simulating the heavy machines models designed with traditional libraries requires step sizes five times bigger than the CPSs generated with ikSimscape.

The novel modelling approach introduced in this library is not exclusively for proportional valves. Fig. 5 compares the parameters necessary to configure a check valve with Simscape library against the model generated in ours. The former requires more constructive parameters, such as the maximum passage area, a problem solved with our alternative, in which the component is easily parametrized with data-sheet information.

A simple case study is presented here to illustrate component assembly of a hydraulic-actuator with ikSimscape. This system shows the capabilities of the library in virtual commissioning methodology. The model, presented in Fig. 6, is composed of a cylinder, a proportional valve, a constant displacement pump, a relief valve and three pipelines. Although the model is quite simple compared with industrial heavy machinery, it allows testing the limitations of the library presented on the paper.

Even though the model is made of few elements, they are high-level hydraulic and mechanical components. Parametrizing them with Simscape^{TM} library requires to acquire constructive parameters obtainable only from laboratory experiments. With ikSimscape, components are easily parametrized with data-sheet information. As it is shown in Fig. 1, the proportional valve is parametrized by means of a point in its flow rate against response time. This information is introduced inside the model parameters, acquiring a similar response as the one plotted in the data-sheet.



Maximum passage area: 1e-4 m^2 Compile-time
Cracking pressure: 0.3e5 Pa Compile-time
Maximum opening pressure: 1.2e5 Pa Compile-time
Flow discharge coefficient: 0.7 Compile-time
Leakage area: 1e-12 m^2 Compile-time
Laminar transition specification: Pressure ratio
Laminar flow pressure ratio: 0.999 Compile-time
Opening dynamics: Include valve opening dynamics
Opening time constant: 0.1 s Compile-time
Initial area: 1e-12 m^2 Compile-time

Switching time: 10 ms Compile-time
Cracking pressure: 0.1 bar Compile-time
Fully open pressure: 0.2 bar Compile-time
Reference differential pressure: 3 bar Compile-time
Reference flow rate: 40 l/min Compile-time
Port volume: 1 l Compile-time

FIGURE 5. **Comparison between the parameters required to define a check valve in ikSimscape (left) and Simscape$^{\text{TM}}$ (right) libraries.**

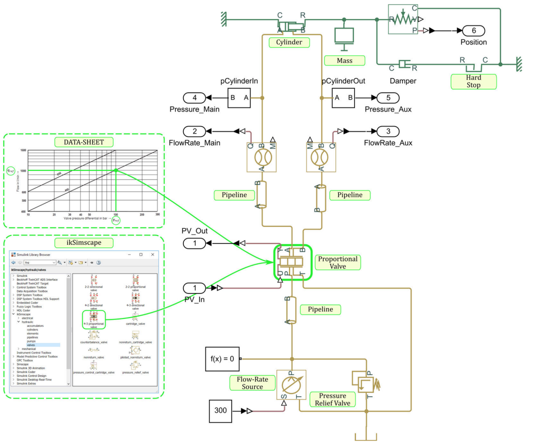


FIGURE 6. **Overview of a simple hydraulic-press made of one cylinder and built up with ikSimscape library.**

C. HIL IMPLEMENTATION

The Cyber-Physical System has been generated under Simulink® environment, which is a non-Real-Time simulation platform. Even thought some options are adjustable to perform a semi-Real-Time simulation, it lacks the robustness of industrial Real-Time targets. On this paradigm, even though Simulink® offers a suitable and easy to use environment for Software in the Loop validation, it does not ensure Real-Time simulations. This disadvantage justify sight for a platform capable to execute the models on Real-Time, that ensures the following characteristics:

- **Cyber-Physical System Export:** Simscape$^{\text{TM}}$ models must be exported without further changes into the platform, in this case, the industrial machines are embedded on the hardware platform without re-parametrizing their components. If any change should be necessary in the model, it must ensure that the response remains identical to the one performed by the real machine.
- **Real-Time Communication:** The model and the controller must be synchronized and communicated through a Real-Time field-bus, that is to say, a deterministic communication protocol is prepared to connect both systems and to send command frames in less time than CPS simulation sample time.
- **Real-Time Visualization:** An easy environment to access controller commands and sensors signals during industrial PC or PLC execution. A platform with these characteristics allows the control designer to easily validate during commissioning stage the input and output signals from the model, reducing the amount of time required to develop control algorithms.
- **Industrial Environment:** The Cyber-Physical System methodology presented in this paper is prepared to model industrial environment components. In this scenario a platform capable of working in this aggressive conditions would be more suitable than the one prepared for the laboratory.

There are multiple devices on the market prepared for HiL validation. Most of the solutions are based on autonomous FPGA systems adapted to simulate models in Real-Time [46]. These systems have been studied and they accomplish with almost every HiL specification: no further reconfiguration is done in the model when it is exported, the communication between controller and model is achieved by EtherCAT or ProfiNET protocol and the industrial machine variables are tracked down during execution time with Simulink® Desktop. Nevertheless, this FPGA systems are prepared for laboratory environment, lacking the robustness necessary to be exported afterwards into the industrial environment.

The industrial solution Beckhof offers is a library prepared to compile and embed Simulink® models in their industrial PCs. This library, which is called TE1400, uses Simulink® Real-Time compiler to generate a TcCOM Object, a program codded with the mathematical equations defining the behaviour of the Cyber-Physical System model. The Simulink® model is compiled and embedded afterwards into TwinCAT 3, Beckhoff developer platform, which brings the following benefits:

- **Build Procedure:** The TcCOM object has similar properties as the initial Simulink® model, so the Cyber-Physical System is exported without modifications.
- **Industrial Field-Buses:** Beckhoff industrial PCs are prepared to support Real-Time communications through deterministic protocols such as EtherCAT or ProfiNET.
- **Dynamic Environment:** TwinCAT 3 offers a visualization environment for TcCOM Objects in which signals are tracked down during execution time in Real-Time.
- **Industrial PC:** As the virtual-twin is embedded in the same platform as the controllers, it is prepared to resist industrial environment.

When the HiL platform is settled-up, the controllers are tested against the CPS model simulated in Real-Time. With this validation, the controllers show their performance in an experiment under similar conditions as the ones they would have on the manufacturing process.

III. HYDRAULIC-PRESS VIRTUAL COMMISSIONING

Novel modelling techniques presented in Section II sight more trustful models capable of reproducing the behaviour of industrial machines. Hydraulic-presses are widely extended on these environments due to their capacities, for instance, moulding or cutting metal pieces. In addition, they are compounded of mechanical, electrical and hydraulic components, which cover most of the physical properties modelled in virtual systems. On Section III-A, the hydraulic-press is presented, explaining the process followed from the real-machine to the CPS model. Section III-B exports the hydraulic-press model into an industrial PC. With this novel procedure a new methodology based in two validation platforms (SiL and HiL) for virtual commissioning in the field of hydraulic-presses has arisen.

A. CYBER-PHYSICAL SYSTEM

Industrial hydraulic-presses are more complex than the case presented in II-B, because they are composed of two main hydraulic parts: an upper one named as slide and a bottom one as cushion. The hydraulic-press presented in this paper has both components and it has been designed to be installed in a manufacturing dedicated to metal sheet stamping (Fig. 7). With blueprint information and following the process described in Section II-B, a virtual model of this hydraulic-press has been integrated in Simulink® environment.

Each component on the metal sheet stamping press has been replicated in this virtual environment, configuring their parameters with the information brought by manufacturer's data-sheet. This hydraulic-press model becomes the CPS of the real machine, as both systems have identical responses.

The **slide**, Fig. 8, is the upper mobile part of the hydraulic-press which is in charge of the top compression force over the metal sheet.

The **cushion**, Fig. 9, is the lower mobile part of the hydraulic-press which is in charge of the bottom compression force over the metal sheet.

Metal sheets are moulded when a force is exerted to them. In the studied case, the hydraulic-press puts forth this force when both cylinders collide. The hydraulic-press cycle comprehends the stages from rest position to the location where force is strained. Even though it is a continuous process, it is divided into seven stages in the case of slide and five for cushion. In each one, the control technique is adapted between closed and open loop, depending in the controlled parameter (Table 5).

In addition, two control strategies are followed and implemented for closed loop controllers, one based on fulfilling a position reference and the other one on a force signal. Proportional valves regulate the flow rate through the cylinder chamber in both control strategies. Table 5 shows which control algorithm has been picked up for the stages in metal sheet mouldering process.

Software in the Loop validation stage brings a suitable environment to design and test the hydraulic-press cycle in a harmless environment. On this case study, Fig. 10 represent a cycle accomplished with the hydraulic-press model. The simulation responds fluidly to the controller signals and performs all the stages in which the metal sheet process is divided.

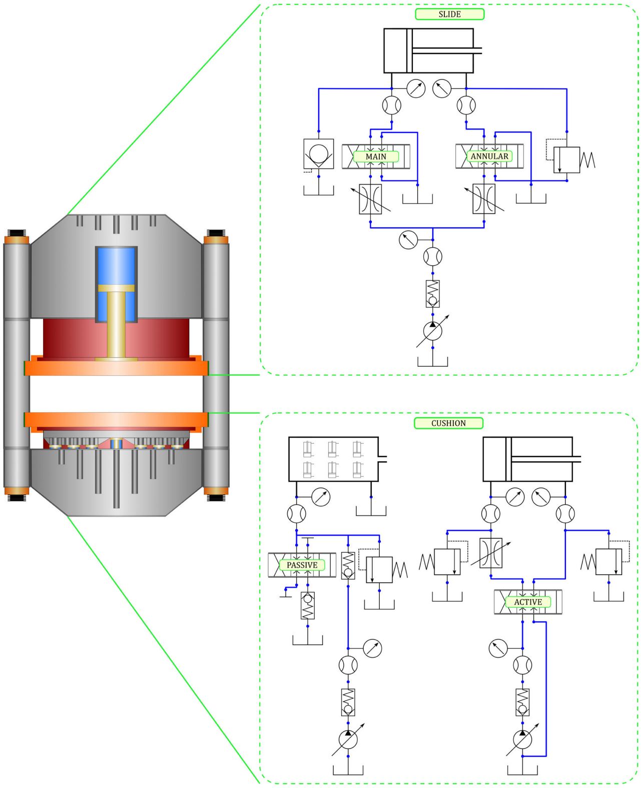


FIGURE 7. Overview of the main components of the hydraulic-press presented on the case study.

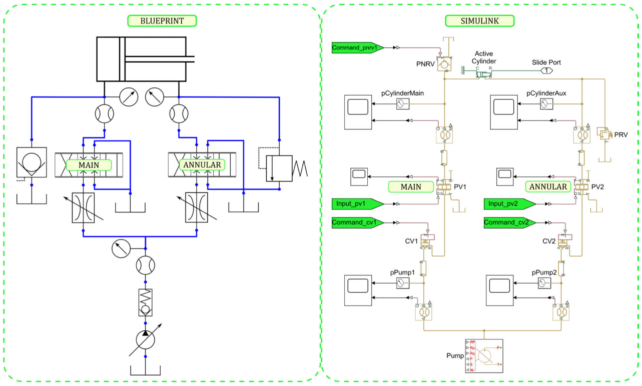


FIGURE 8. From blueprint to Simulink®, generation of the slide Cyber-Physical System, compounded of one active cylinder.

TABLE 5. Type of controller selected for each stage in the hydraulic-press cycle.

SLIDE			CUSHION		
Stage	**Main Chamber**	**Annular Chamber**	**Stage**	**Active Cylinder**	**Passive Cylinder**
Free fall	Open Loop	Position Closed Loop	Pre-Acceleration	Position Closed Loop	Open Loop
Chamber transition	Open Loop	Open Loop	Packaging	Force Closed Loop	Open Loop
Work fall down	Position Closed Loop	Open Loop	Making force	Open Loop	Force Closed Loop
Making force	Force Closed Loop	Open Loop	Decompression	Position Closed Loop	Open Loop
Decompression	Open Loop	Open Loop	Normal recovery	Position Closed Loop	Open Loop
Slow recovery	Open Loop	Open Loop	Pick-Up recovery	Position Closed Loop	Open Loop
Fast recovery	Open Loop	Position Closed Loop	Accompaniment recovery	Force Closed Loop	Open Loop

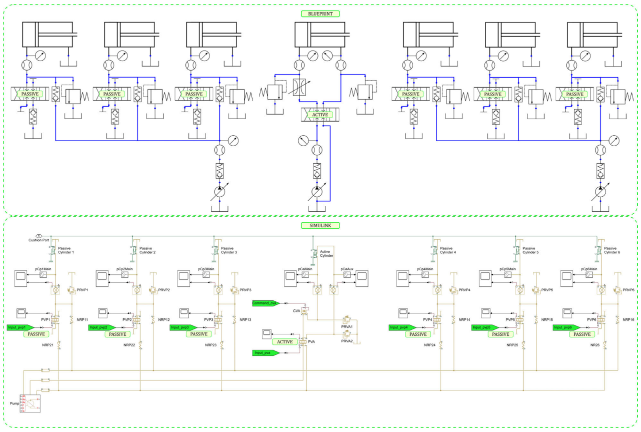


FIGURE 9. From blueprint to Simulink®, generation of the cushion Cyber-Physical System, compounded of six passive cylinders and one active.

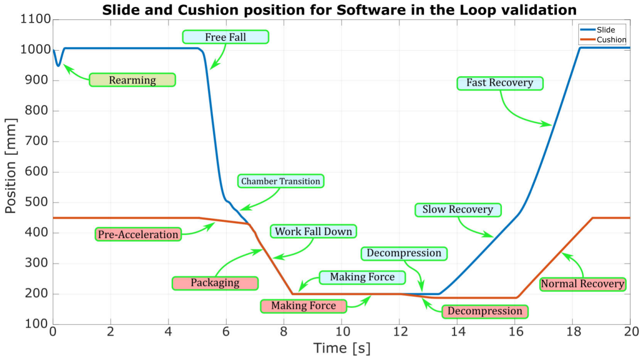
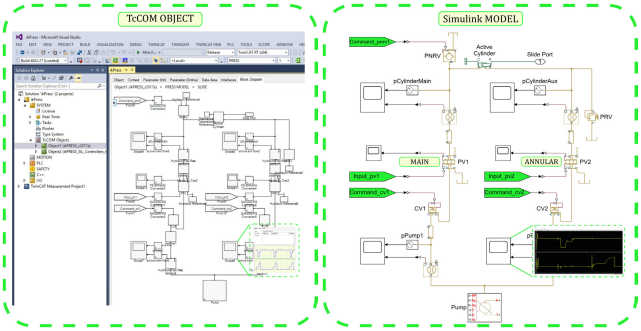


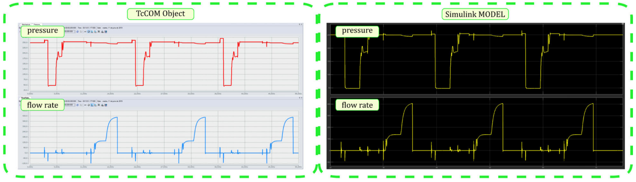
FIGURE 10. Software in the Loop simulation: Hydraulic-press cycle with slide and cushion stages tagged.

B. HARDWARE IN THE LOOP

When the hydraulic-press model has passed the SiL validation, the Cyber-Physical System is embedded under a Real-Time platform to begin a new set of tests under a Hardware in the Loop validation platform. In the case studied in this paper, a Beckhoff Industrial PC has been selected as the target system, due to the benefits exposed on Section II-C. With this platform, the hydraulic-press conditions on the manufacturing process are replicated. The controllers are designed with this hardware and tested against the Cyber-Physical System, which is simulated in Real-Time similarly as a control designer would do during commissioning process. Both systems, plant and controller, are communicated through a deterministic communication protocol, ensuring the Real-Time capabilities during validation phase.



(a) TwinCAT 3 hydraulic-press Cyber-Physical System (b) Simulink® hydraulic-press Cyber-Physical System



(c) Pressure and flow rate responses

FIGURE 11. Comparison between the CPS generated in Simulink® against the TcCOM Object from TwinCAT 3.

The model has been embedded into TwinCAT 3 as a TcCOM Object [27], establishing the hardware platform prepared to design and configure control algorithms. Fig. 11 shows the slide hydraulic circuit generated with Simulink against its version exported into a TcCOM Object. As it is observed, each component designed in Simulink® has been replicated in TwinCAT 3, performing an identical behaviour independently of the platform.

During Software in the Loop validation phase, an initial approach to control design has been done, as primitive controllers were used to test the model. Even thought, they were suitable for this validation platform, they were designed exclusively with MATLAB® control toolbox. In Hardware in the Loop validation stage, TwinCAT 3 brings new control libraries. They contain useful tools and common control architectures to regulate industrial actuators. In the case studied in this paper, MATLAB® control toolbox and Beckhoff control library are mixed to maximize their benefits.

The first steps in control design, plant identification and controller gains adjustment are studied under MATLAB® and Simulink® during SiL validation. A plant model has been studied for each control loop in the hydraulic-press cycle. As it has been exposed in Table 5, each stage has their own type of control loop, so each one has been studied independently, discerning if the closed loop controller follows a force or a position reference. For instance, in free fall stage the slide only requires a position closed loop control for annular chamber, so an experiment was carried out to determine control gains for the proportional valve in charge of regulating flow rate through it to obtain their plant transfer function. Main chamber, as it requires an open loop controller, was configured with a fixed opening during the experiment, which matches the value used when the real hydraulic-press performs its nominal cycle in the manufacture. After these experiments, each stage of the hydraulic-press cycle was characterized and a plant model for each one is available (Table 6):

TABLE 6. **Plant identified in each control loop for the hydraulic-press cycle.**

Chamber	CL	Transfer Function
Main	Position	$G(s) = \frac{1793.3}{1+6.9\cdot10^{-2}s+2.6\cdot10^{-3}s^2}e^{-3.7\cdot10^{-2}s}$
	Force	$G(s) = \frac{6.1\cdot10^{6}}{1+0.2s}$
Annular	Position	$G(s) = \frac{-472.6}{1+1.22\cdot10^{-2}s+9.4\cdot10^{-5}s^2}e^{-9.2\cdot10^{-3}s}$
Active	Position	$G(s) = \frac{430.6}{1+3.4\cdot10^{-2}s+4.04\cdot10^{-5}s^2}e^{-8.3\cdot10^{-3}s}$
	Force	$G(s) = \frac{1.7\cdot10^{6}}{1+6.6\cdot10^{-3}s+1.7\cdot10^{-4}s^2}$
Passive	Force	$G(s) = \frac{1.9\cdot10^{6}}{1+0.5s+1.0\cdot10^{-2}s^2}$

After plant identification phase, the controllers are designed in three stages:

1) **Simulink® Gains:** Controller gains are obtained with the aid of MATLAB® control toolbox. One PID controller has been designed for each plant identified in the hydraulic-press cycle (Table 6). These controllers are tested in this software environment before they are exported to TwinCAT 3.
2) **State Machine:** The hydraulic-press performs a periodic cycle, as it has been shown in Fig. 10. A state machine control algorithm has been designed in TwinCAT 3 to represent each stage of this process, that is to say, for each one of the stages setted out in Table 5 a case has been implemented in the state machine.
3) **Commands:** These controllers discern the type of closed control loop (position or force) during the current hydraulic-press cycle stage, changing position controller to force harmless for the machine. In addition, they regulate the command signals for the proportional valves (in open loop control), the safety valves (piloted non-return valve) and the cartridge valves, which are adapted by the control designer during virtual commissioning.

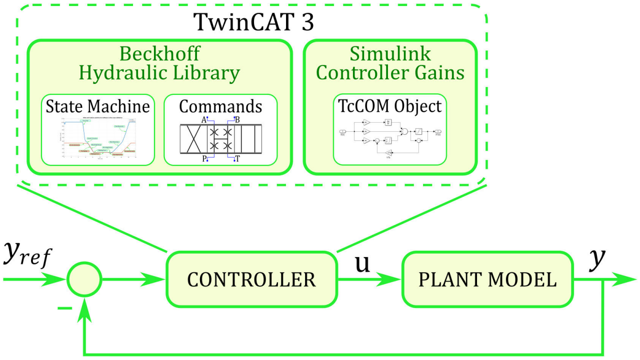


FIGURE 12. **Control loop combining algorithms designed with MATLAB® control toolbox and Beckhoff hydraulic library.**

As a summary, Fig. 12 represents the control loop followed in the studied hydraulic-press cycle. The Cyber-Physical System, has been modelled in Simulink® with the aid of a library based on Simscape™language, nonetheless the three controllers have been designed in two stages, one with MATLAB® control toolbox and the other with Beckhoff hydraulic library. This last stage has two control techniques, one with the hydraulic-press cycle state machine and the other one with the control commands for the valves. Finally, the three controllers have been embedded under the same platform, TwinCAT 3, in order to perform the Real-Time simulation under a Hardware in the Loop validation platform.

When the HiL platform is settled-up, the controllers are tested against the Cyber-Physical System hydraulic-press in Real-Time. The controllers, in order to prove their performance in similar conditions to the ones they would have on the manufacture, are connected through a deterministic communication protocol with the hydraulic-press model. Nowadays, there are multiple options based on Ethernet Real-Time with this characteristic, as the study in Section II-C reflects.

EtherCAT, as a deterministic communication protocol, has been selected to communicate the controller and the hydraulic-press, while ADS (Beckhoff naive deterministic communication protocol), connects the three control algorithms embedded on TwinCAT 3. In order to clarify this situation, Fig. 13 shows the communication protocols in each stage of the HiL validation platform.

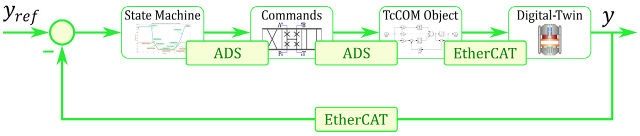


FIGURE 13. **Communication field-bus selected to connect the controllers and the Cyber-Physical System.**

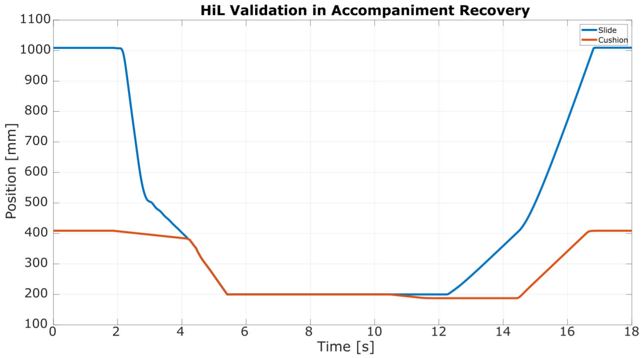


FIGURE 14. Hydraulic-press cycle obtained in Hardware in the Loop validation with Cushion in Normal recovery mode.

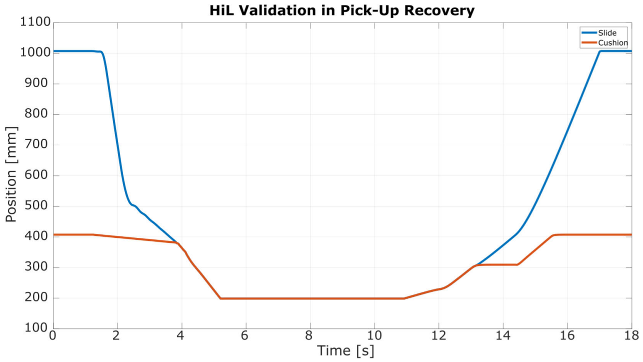


FIGURE 15. Hydraulic-press cycle obtained in Hardware in the Loop validation with Cushion in Pick-Up recovery mode.

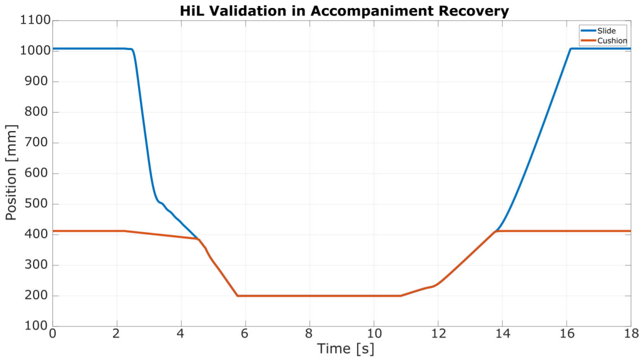


FIGURE 16. Hydraulic-press cycle obtained in Hardware in the Loop validation with Cushion in Accompaniment recovery mode.

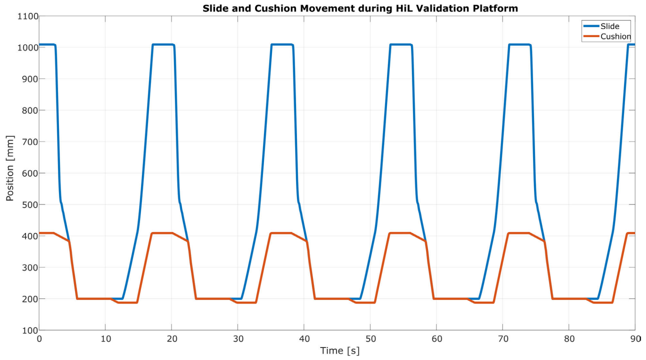


FIGURE 17. Hydraulic-press cycle simulated constantly under the Hardware in the Loop validation platform.

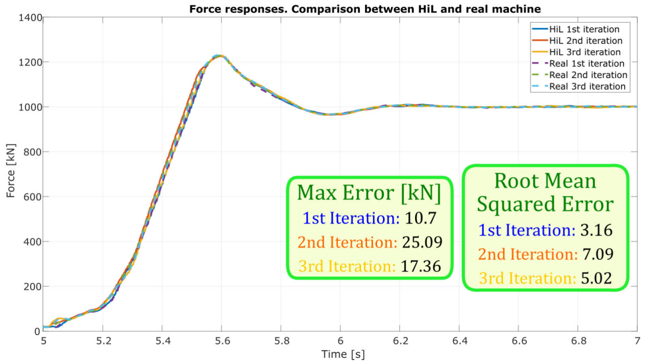


FIGURE 18. Comparison between the response obtained in the real system and the virtual model generated with ikSimscape library.

On this Hardware in the Loop validation platform, the controllers are tested against the hydraulic-press CPS. Fig. 14 shows the press performance during this validation. As it is appreciated, the slide and cushion performs each stage in the hydraulic-press cycle, from rest position to making force. Afterwards, another set of validations have been done, modifying the recovery process to one of the cases presented in Table 5, that is to say, Fig. 15 and Fig. 16 represents pick-up and accompaniment recovery respectively.

When the hydraulic-press model and the controllers have been validated under the HiL platform, the virtual commissioning process is finished. The controllers designed during this phase are easily exported to a real machine, as their behaviour has been probed against a Cyber-Physical System performing identical responses as a real hydraulic-press. In addition, these changes are done off-line without stopping the machine installed on the manufacturing process. As a last overview of the possibilities of this HiL methodology, in Fig. 17 the hydraulic-press has been tested under manufacturing conditions. In this case, the hydraulic-press performs a periodic cycle instead of a standalone simulation, showing how the system responds when the controllers designed are exported to the real process without further modifications.

Fig. 18 compares force responses obtained on the real system against the simulation carried out on the HiL platform. The experiment simulates three hydraulic-press cycles comparing their responses. As this final validation shows, the model responses are similar to the ones acquired from the real machine. This statement allows to export the controller designed under laboratory conditions to the real hydraulic-press without further modifications, as the behaviour of the CPS is identical to the real one.

IV. CONCLUSION

On this paper a novel methodology prepared to accomplish the virtual commissioning of industrial machines has been presented, sighting to reduce the associated costs.

To deal with this problem, the paper exposes a new methodology based on generating virtual models of these heavy machines, called CPSs, and test the controllers under two validation platforms, one based only in software technology (Software in the Loop) and the other one on hardware and software technology (Hardware in the Loop). This methodology sight for Real-Time models capable of reproducing an identical performance as the industrial machines, executing them in real-time with short simulation steps. On this context, a novel modelling technique is presented to design high level industrial components and configure them through parameters obtainable from data-sheets. They perform an identical response as the one described by manufacturers on this technical documents, without the necessity of slowing down the simulation, that is to say, in Real-Time. The industrial machines designed with this novel technique are tested initially under a SiL validation platform, validating the feasibility of the model. Afterwards, the Cyber-Physical System is exported into a hardware prepared for industrial environment and communicated through a deterministic communication protocol with the hardware in which the control algorithms are implemented. This procedure allows to replicate the commissioning process in laboratory environment, due to the fact that controllers are tested against a digital-twin simulated in Real-Time.

During Section III, the methodology has been tested with a case study of a hydraulic-press prepared for metal-sheet stamping. It has been modelled with this methodology and introduced in a library that enables the creation of the Cyber-Physical System just by dragging and dropping components and parametrizing them following data-sheet information. During SiL validation, it has been corroborated that the performance achieve by the CPS is similar to the one a real hydraulic-press would have. Subsequently, it has been embedded into an industrial PC, in which the control algorithms have been developed. Via a deterministic communication protocol, the controllers have been connected to the virtual plant, allowing to test them in a harmless environment with a virtual commissioning methodology. Afterwards, when the validation phase has ended, they are exported onto the real system and connected to them without further modifications. This methodology brings plenty of benefits, improving and reducing the cost associated with controller modification and commissioning for industrial machines.

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