Real-time HiL for Hydraulic Press Control Validation

J. Rodríguez[1], C. Calleja[1], A. Pujana[1], I. Elorza[1] and I. Azurmendi[2]
[1]IK4 – IKERLAN Technology Research Centre, 20500 Arrasate-Mondragon, Gipuzkoa, Spain
[2]KONIKER S. KOOP., Apdo. 18, San Andres auzoa, 20, 20500 Arrasate-Mondragon, Gipuzkoa, Spain

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Abstract: Hydraulic press control validation often competes for access time with other logistical and production needs. This can result in significant costs due to down times, longer delivery periods and sub-optimal control adjustments. Reduction of said costs has traditionally been pursued via some degree of virtual commissioning, i.e. control validation away from the press, via a model. All such models require a compromise between cost, fidelity and simulation time. Here, we present a case study in which we have achieved a low-cost, high-fidelity, real-time hydraulic press model, with a flexible methodology which allows model creation in parallel with the engineering stage, as well as easy model refinement and modification during the entire press lifecycle.

1 INTRODUCTION

Commissioning results in a non-negligible part of the overall cost of hydraulic presses, due to the considerable number of man-hours and factory floor occupancy it incurs. This is only exacerbated by its taking place at the end of press deployment projects - or even years later, when retrofitting or improvements are carried out - and largely on site, often thousands of miles away from the manufacture's infrastructure (Vilacoba, D.[a] et al., 2016 and Qiu, X. et al., 2016).

It is currently possible to considerably reduce the cost and risk of commissioning via software tools which allow different levels of hydraulic design and controller validation. However, further integration and streamlining of the design, validation and commissioning processes are yet worth seeking, in order to avoid costly and error-prone model and controller refactoring, as well as closing the gap between simulations and real press operation.

Real-time capability on the part of reasonably high-fidelity hydraulic models is a necessity for virtual commissioning. Solutions exist in which controller execution times are slowed down to synchronise with slower than real-time models. However, this makes it difficult to account for communication delays and processing times during validation.

It is also essential for virtual commissioning that it be possible to build models at the systems engineering level, i.e. based on component specifications, rather than constructive details or undocumented physical properties. This is typically catered to via component model catalogues compiled by component manufacturers. However, this results in considerable fragmentation of component modelling efforts and makes it all the more difficult for the systems engineer to model circuits combining components from manufacturers whose component model catalogues have different formats.

A methodology is therefore sought for real-time capable, component manufacturer independent, hydraulic circuit modelling at the systems engineering level, which provides sufficient fidelity for virtual commissioning and spans the entire product lifecycle.

Hydraulic circuit modelling is widely present in the literature, where the most common approach is based on Modern Control Theory. (Zadeh, L. et al., 1963, Jung, D.[a] et al., 2014 and Respondek, J.S., 2010). This theory was employed to develop hydraulic circuits with complex nonlinear equations, far away for the idea to create low complexity and data-sheet level hydraulic components.

OpenModelica provides a systematic and convenient way to manage this sort of nonlinear equations. The model equations were not designed

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for a full hydraulic circuit, instead each component has its own set of equations. The hydraulic circuit model was achieved combining these individual components following the press schematic on the blueprints.

Once the hydraulic circuit has been modelled, it is time to start the control design and the validation process. The virtual representation of the press and industrial PC controller compound has been achieved connecting the model ports to the input and output ports of the controller.

On a Software in the Loop (SiL) validation the reaction between the hydraulic models and the controller will be tested in order to debug them. On a Hardware in the Loop (HiL) validation, the controller will be embedded on the hardware, verifying how it will react during the commissioning.

This paper discusses the steps to develop from the controller design to the virtual commissioning. After this explanation, the focus will be centred in analysing the real-time modelling, validating the hypotheses first with a simple hydraulic press and second with a more complex industrial press. Finally on the conclusions, we will discuss the final results and set out the future work in this virtual commissioning study.

2 FROM CONTROLLER DESIGN TO VIRTUAL COMMISSIONING

Simulink® is an interesting controller design tool, especially due to a growing number of control hardware manufacturers supporting code generated directly from Simulink® projects. This allows seamless verification at every stage of the engineering and commissioning processes:

- **Design:** during the design phase, the press model is integrated within the same Simulink® project as the control blocks. This allows flexible and dynamic testing of new algorithms and architectures.
- **SiL Validation:** once the control algorithms are ready for validation, the press model is taken out of the Simulink® project, and the control algorithms are tested as a stand-alone piece of software, which communicates with the press model for co-simulation. This provides a software-in-the-loop validation framework.
- **HiL Validation:** once the control algorithms are validated, the Simulink® project is embedded in an industrial controller, while the press model is run in real time and communicated with said controller. This provides a hardware-in-the-loop validation framework (Crăciun, O.[a] et al., 2014).
- **Virtual Commissioning:** once the controller is validated, it is wired to a real-time target running the press model, e.g. via a field bus or analog signals. This provides a framework for controller commissioning, after which it may be directly wired to the physical press. At this point, any further necessary adjustments come from unmodelled press properties.

This controller lifecycle requires a press modelling methodology which allows model creation based on drawings and specifications, and integrates well with Simulink® during the design phase. It must also result in real-time-capable models, which can be directly used during HiL validation and virtual commissioning.

3 REAL-TIME MODELLING

The modelling of hydraulic presses at the system level is most conveniently done with sets of algebraic differential equations, which are given by classical mechanics and hydraulics. Multiple software tools are currently available which aid this modelling process, as well as solving the resulting sets of equations. Said tools are based on component libraries, elements from which are combined and linked to define full models (Skoglund, T.[ab] et al., 2007 and Winter, M.[a] et al., 2015).

We have chosen to work with OpenModelica (Fritzson, P., 2011), due to its being Open Source, which provides good cost-effectiveness, flexibility and price stability. It will also be shown that it provides every feature we need for our virtual commissioning methodology (Linköping, 2014).

Regarding component libraries, the same reasons may have driven us to choose the standard Modelica library, or another of the available free ones. However, they have one or more of the following disadvantages:

- **Excessive Complexity:** e.g. the standard Modelica library uses multi-phase fluids. This is necessary to model refrigerators, but little more than a computational burden when modelling hydraulic presses.

- **Constructive Parameters:** e.g. valves are often modelled based on passage areas. This is useful to design valves, but impractical when modelling full hydraulic circuits based on commercial components. As a result, models based on these libraries require a backward-engineering process, in which nominal component flow characteristics are reproduced via trial-and-error adjustment of constructive parameters.
- **Excessive fidelity**: e.g. valves are often modelled for fidelity with both laminar and turbulent flows (Gavrilakis, S., 1992). This results in full circuit models whith a sort of fidelity which is very difficult to validate when designing said circuits, because component data sheets do not provide the information that would be necessary to determine the critical flow rate. It also results in very slow models.

As a result of these disadvantages, we have chosen to write our own OpenModelica library, to fit the specific needs of our use case. We have then used that library to model a state-of-the-art hydraulic press.

3.1 Hydraulic Component Library

We seek a library with the following characteristics:

- **Low complexity:** the library must be easy to use, and therefore made of high level hydraulic components, such as valves, pumps, cylinders and pipelines. Low level details such as pilot lines must be abstracted. This will allow high-level integration of complex models at the system design phase, rather than component design.
- **Datasheet-level Parameters:** components must be configurable by simple inspection of data sheets. Passage areas and other constructive details must be abstracted, because they are not easily deduced from data sheets. This will allow direct component configuration at the system design phase, and avoid modelling via reverse engineering.
- **Datasheet-level Fidelity:** components must behave as specified by data sheets. Fidelity beyond the level specified by data sheets must be avoided. This will allow model validation via direct comparison with parameters, and minimise computation time for the maximum level of fidelity which is verifiable at the system design phase.

We develop and maintain a library for OpenModelica with these characteristics (Figure 2). The library models the main hydraulic and mechanical components we typically find in industrial presses, such as cylinders, valves, pipelines and pumps (Adiprasetya, M.H., 2012).

All components are configurable via parameters typically found in data sheets, such as nominal flow rates, piston areas or response times. Figure 1 shows a flow rate diagram given by a proportional valve data sheet. A single point taken from said diagram is enough to configure our corresponding component, which results in the simulation also show in the figure.

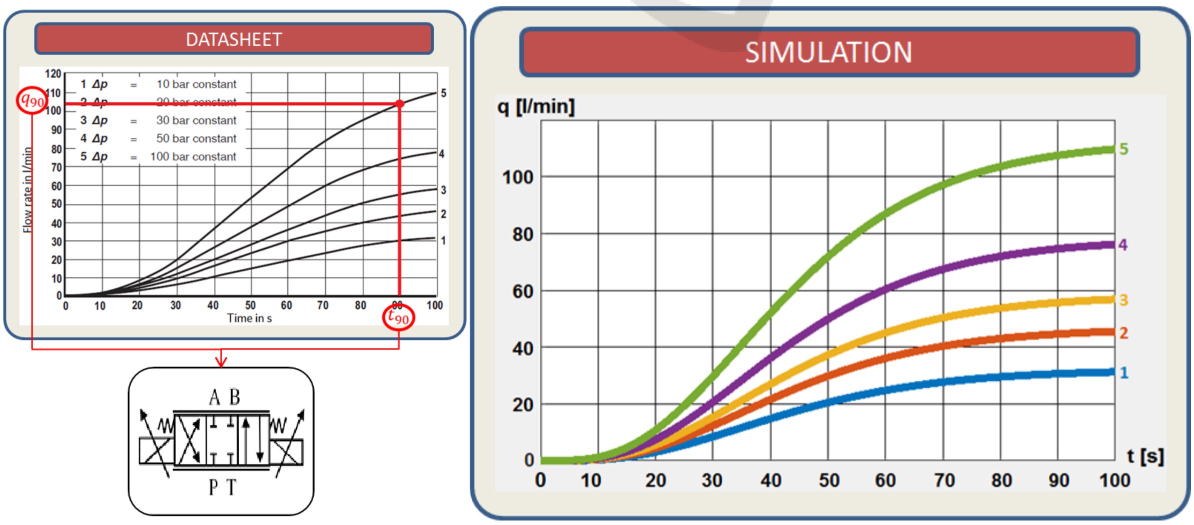

Figure 1: Proportional valve model configuration and simulation results.

3.2 Model Assembly

A simple case study is presented here to illustrate circuit model assembly from the components in our OpenModelica library. Figure 3 shows a model with a cylinder, a proportional valve, a constant displacement pump, a relief valve and three pipelines. The cylinder pushes on a considerable mass and, when extended sufficiently, comes in contact with a damper, which may be a simple representation of a deep drawing process. Model assembly is done by dragging and dropping components from the library, and configuration is done from data sheets (Madin, B.[a], 2016).

Although this model is rather simple compared to typical hydraulic presses, it will give a taste of the fidelity which is achievable with our library, while still maintaining real-time capabilities with complex models, as will be shown in section 0.

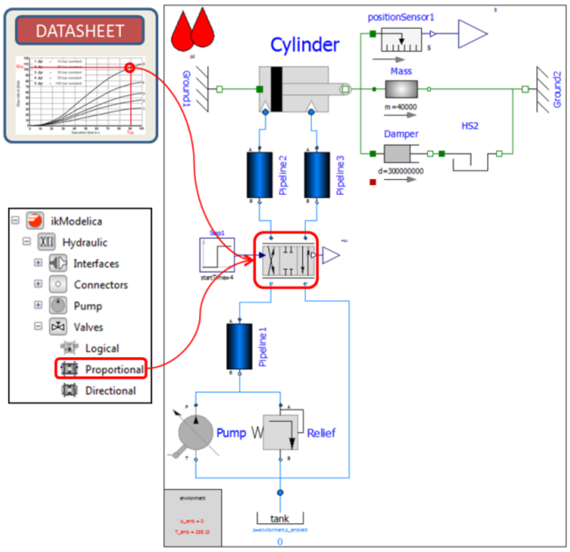

Figure 3: Simple model.

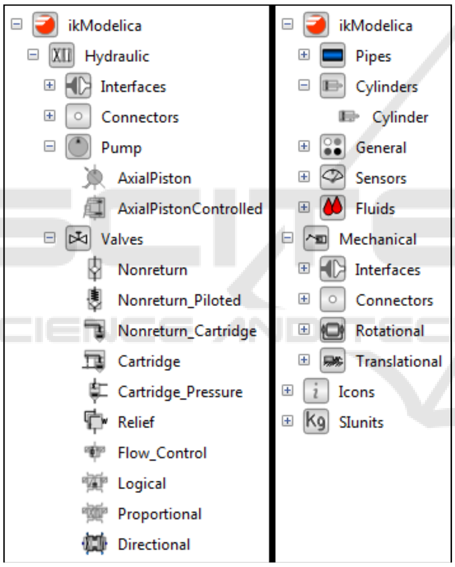

Figure 2: Our OpenModelica library.

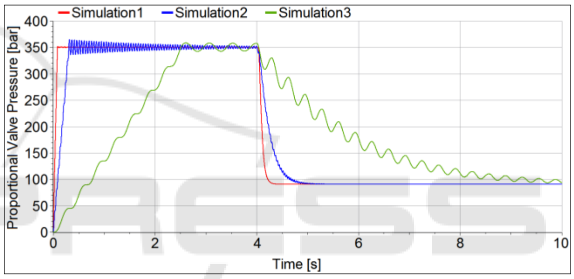

Figure 4: Proportional valve port P pressure.

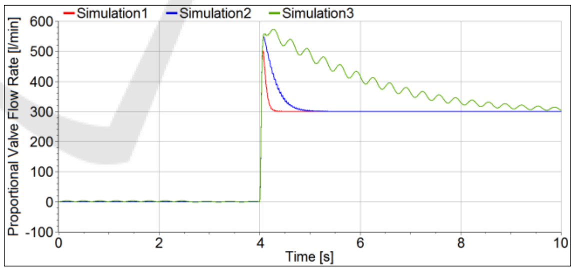

Figure 5: Proportional valve port P flow rate in litres per minute.

Figure 4 shows the pressure at the P port of the proportional valve during three different 10 second simulations, the difference between which is the length of the pipeline coming from the pump. Simulations 1, 2 and 3 correspond to pipeline lengths of 1, 10 and 100 meters, respectively. Note that the pressure is initially 0 and, since the proportional valve is closed, it grows as the pump compresses oil into the pipeline. The pressure stabilises at 350 bar, where the relief valve opens to limit it. As pipeline length grows, pressure takes longer to build up and oscillations appear.

4 seconds into the simulations, the proportional valve is fully opened to make the cylinder extend. Then, oil flows from the pump to the cylinder, and pressure at port P goes down to the pressure differential needed to get the pump's nominal flow rate through the valve. Again, pressure drops slower and in a more oscillating way as pipeline length grows. This is due to the pipeline acting as a pressurised reservoir, which requires more oil to flow through the valve to drop a given pressure, as shown by Figure 5.

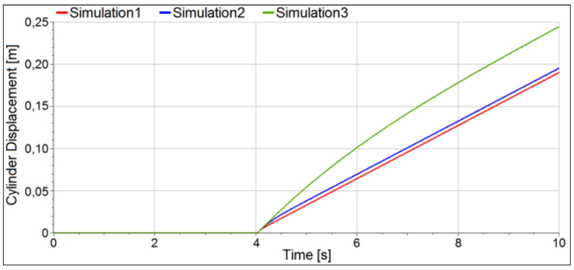

Figure 6: Cylinder displacement.

Figure 6 shows the cylinder displacement. Initially, it is fully retracted and, 4 seconds into the simulations, when the valve opens, it extends. The pipeline going from the pump to port P on the valve acts as an accumulator, and provides an initial boost, which gets larger as the pipeline gets longer. The cylinder subsequently settles to a constant speed, dictated by the pump's nominal flow rate.

Figure 7 shows what happens afterwards. The cylinder continues to extend until it makes contact with the damper. This results in the cylinder extension slowing down to a speed dictated by maximum pump pressure and valve flow characteristics. Note that pressure buildup in the longer pipeline requires a longer time, which results in the cylinder displacement in simulation 3 again getting closer to that of simulations 1 and 2.

4 VALIDATION CASE STUDY

4.1 Press Model

For the case study presented here, a hydraulic press circuit based on a commercial press has been modelled, which uses a subset of the components in the library described by section 0.

The model has been assembled exactly as the circuit design drawings are, i.e. by placing all components on a graphical interface and connecting the ports. Component parameters have then been directly taken from publicly available component data sheets. Without further abstraction or simplification efforts, the model is real-time capable and provides as much fidelity as is possible to validate with the available design data.

The press model features 9 cylinders, 9 proportional valves, 2 pumps, multiple non-return, pressure relief and cartridge valves and multiple pipelines.

A controller has been implemented in Simulink®, based on the original press controller, which is implemented on traditional motion control hardware. This has allowed the parallel model and controller development described in section 0.

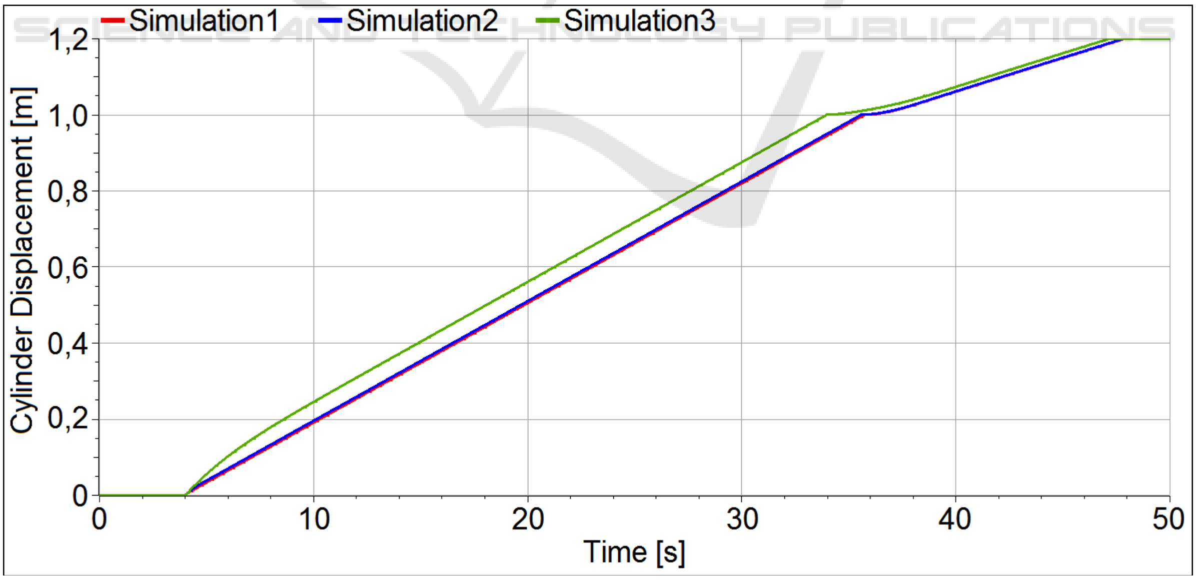

Figure 7: Cylinder displacement until contact is made with damper.

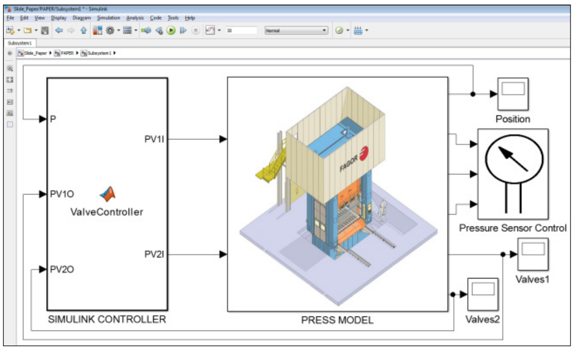

Figure 8: Software in the Loop validation.

The press model has been included in the Simulink® project via a functional mock-up unit (FMU) for co-simulation (Chen, W.[a] et al., 2011). The Simulink® control algorithms have then been run in parallel with the press model, and adjusted based on control response until the latter has been considered appropriate.

4.2 Hardware-in-the-Loop

The validated Simulink® control algorithms have been embedded in the Beckhoff industrial PC shown by Figure 9, via its real-time system TwinCAT 3. This would be their definitive form for commissioning. However, HiL validation is possible, due to the press model's real-time capability (Sun, P. et al., 2002; 2005; 2006 and Ferreira, J.A.[a] et al., 1999).

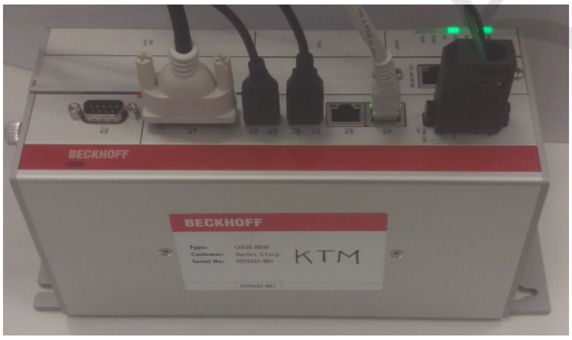

Figure 9: Industrial PC used for HiL validation.

The press model has been separated from the control algorithms, and communicated with the latter via TwinCAT's ADS blocks. Running on the Windows CPU of the industrial PC, it keeps up with the real-time execution of the control algorithms on TwinCAT, and generates the sensor signals based on the press dynamics and the commands it receives from the controller.

A Simulink® project has been created to build the TcCOM object and export the controller from this software into TwinCAT. This method connects Simulink® blocks directly to the PLC syncrhonizing both clocks in real-time. The controller was exported as a S-Function with a similar behaviour of the initial control (Figure 10).

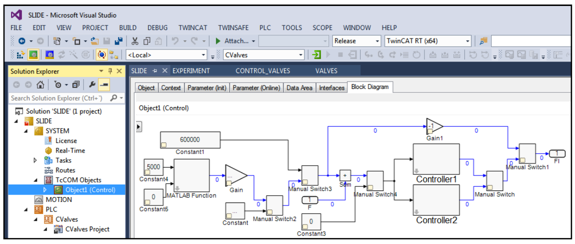

Figure 10: TcCOM Object with the controller developed in Simulink® and embedded in TwinCAT 3.

TwinCAT is capable of executing this module in real-time assigning a task. This process is similar to the one followed by the PLC to create and run the Program Organization Units (POU's) and the main program. The TcCOM Object execution time was configured in the task, and has to be similar to the one selected in Simulink® during the design stage.

The HiL methodology was developed connecting the TcCOM Object with the Simulink® simulation. In this project, the controller was replaced with a "*TC ADS Symbol Interface*" capable of communicating Simulink® simulation with the controllers running in TwinCAT (Figure 11).

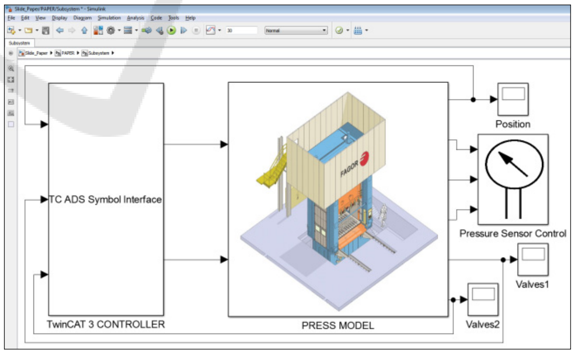

Figure 11: Hardware in the Loop validation.

The results of both SiL and HiL validations are in this case similar, as expected. Some variables are shown by Figure 12 and Figure 13. Note that pressure response times and oscillations are determined by valve response times, pipe dimensions, oil compressibility, head losses and, in general, by all the circuit characteristics which are specified by the hydraulic design documentation.

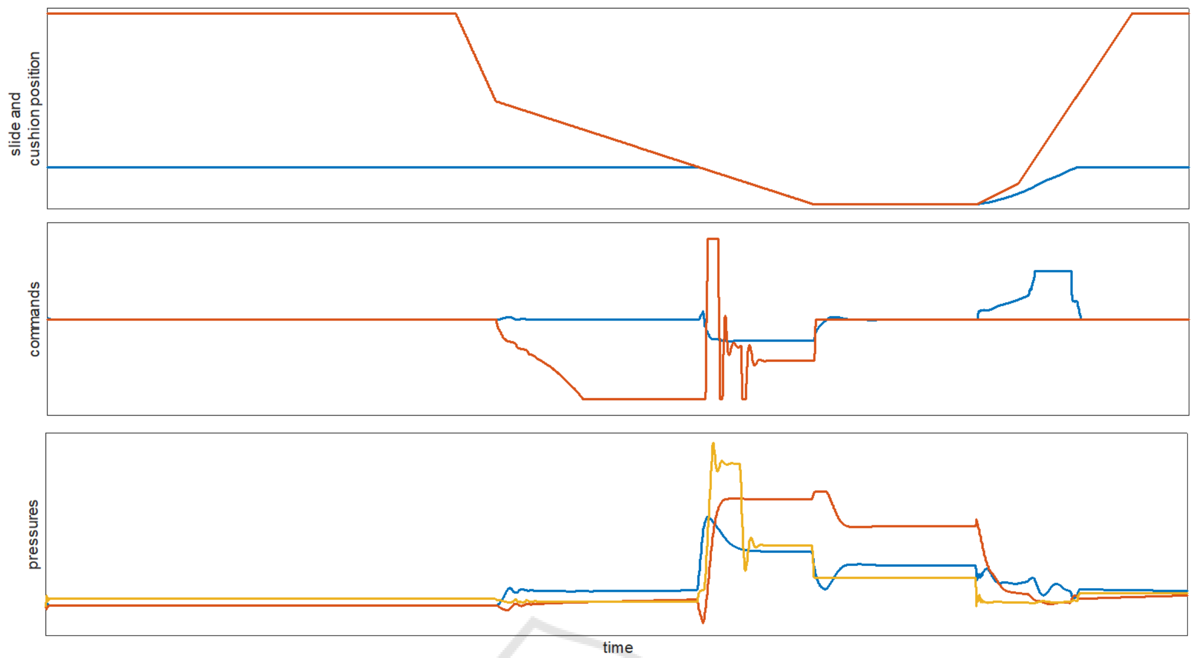

Figure 12: Validation results.

After this HiL validation, the controller is ready for deployment on the press, pending the configuration of the industrial PC for communication with its instruments. However, a virtual commissioning is possible, in which the press model is moved to a system capable of physically replicating all the sensor and actuator communications and signals. This, due to its relative cost in terms of input and output cards necessary for said system, has been excluded from this case study, and is reserved for actual press commissioning processes, where the savings generated by the virtual commissioning outweigh its cost.

5 CONCLUSIONS

A modelling methodology is sought for hydraulic press virtual commissioning. Full integration with engineering processes and real-time capabilities are the primary requirements.

It has been argued here that said methodology can profit from existing physical modelling packages, among which is OpenModelica. Existing component libraries are however not generally focused on virtual commissioning and systems engineering needs, and do not therefore typically fully accomodate said requirements.

We develop and maintain an OpenModelica library which specifically targets virtual commissioning and allows high-fidelity modelling of hydraulic presses, based on publicly available data sheet parameters, at every stage of the development cycle, including real-time HiL validation.

Some of said libary's characteristics and capabilities have been presented here, and a case study has been described, in which a commercial hydraulic press model has been run on a Beckhoff industrial PC for controller HiL validation.

This methodology integrates well with the controller development cycle. However, it requires an additional effort to model presses in OpenModelica. As it has been argued, said effort is moderate, it accomodates the systems engineering skillset and provides a sufficient reward in terms of cost and risk reduction. However, it fragments the systems engineering efforts, because circuit design is duplicated, since OpenModelica is not sufficient to produce all the necessary system documentation, e.g. hydraulic drawings.

Further integration is therefore sought with the system design tools, in order to draw circuit design details from a centralised repository and produce models automatically, thus reducing specific modelling efforts during press development and eliminating error-prone manual configuration. In future works,we will reinforce this methodolgy by means of automatizing the process with OpenModelica Python Interface.

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REFERENCES

Vilacoba, D.[a], Perez, P.[a], Gracia, A.[a], Weber, P.[b], 2016. Conference Paper, Optimized press line orchestration through virtual prototyping: A successful story in, *IEEE International Conference on Industrial Technology, ICIT 2016*, IEEE Xplore.

Qiu, X., Xiao, C., Tan, H., Hou, Y., Zhou, Y., 2016. Article. Multi-software co-simulation for a large robotic automatic stamping production line, in *China Mechanical Engineering*.

Zadeh, L., Desoer, C., 1963, *Linear System Theory: The State Space Approach*. McGraw Hill, New York.

Jung, D.[a], Kang, D.[b], Kang, M.[c], Kim, B.[c] , 2014. Article. Real-time pump scheduling for water transmission systems: Case study, in *KSCE Journal of Civil Engineering*, Springer.

Respondek, J.S., 2010. Article. Numerical simulation in the partial differential equation controllability analysis with physically meaningful constraints, in *Mathematics and Computers in Simulation Volume 81, Issue 1 September 2010 Pages 120-132*, Elsevier.

Crăciun, O.[a], Florescu, A.[a], Munteanu, I.[b], Bacha, S.[a], Radu, D.c, 2014. Article. Hardware-in-the-loop simulation applied to protection devices testing, in *International Journal of Electrical Power and Energy Systems*, Science Direct.

Skoglund, T.[ab], Dejmek, P.[a], 2007. Article. A dynamic object-oritented model for efficient simulation of fluid dispersion in turbulent flow with varying fluid properties, in *Chemical Engineering Science Volume 62, Issue 8, April 2007, Pages 2168-2178.* ELSEVIER.

Winter, M.[a], Taube, J.[a], Froeschl, J.[b], Herzog, H.-G.[a], 2015. Conference Paper. From Simulation to Testbench Using the FMI-Standard, in *12th IEEE Vehicle Power and Propulsion Conference.* IEEE.

Fritzson, P., 2011. Conference Paper. Modelica A cyber-physical modeling language and the OpenModelica environment, in *7th International Wireless Communications and Mobile Computing Conference*, IEEE Xplore.

Linköping, 2014. *Modelica® - A Unified Object-Oriented Language for Systems Modelling*, Modelica Association, Version 3.3 Revision 1.

Gavrilakis, S., 1992. Article. Numerical simulation of low-reynolds-number turbulent flow through a straight square duct, in, *Journal of Fluid Mechanics*, Journal of Fluid Mechanics.

Adiprasetya, M.H., Prihatmanto, A.S., 2015. Conference Paper. Design and implementation of real time simulator with Modelica, in *2012 International Conference on system Engineering and Technology.* IEEE.

Madin, B.[a], Ausiin, R.[b], 2016. Conference Paper. Case studies of the design and performance of one-way surge tanks in pumped water and wastewater pipelines, in *12th International Conference on Pressure Surges*, BHR Group Limited.

Chen, W.[a], Huhn, M.[a], Fritzson, P.[b], 2011, Conference Paper, Pages 19-24. A generic FMU interface for modelica, in *Proceedings of the 4th International Workshop on Equation-Based Object-Oriented Modelling Languages and Tools*, EOOLT 2011.

Sun, P., Talaia, P.M., Rocha, A.M., Grácio, J.J., Ferreira, J.A., 2002, Conference Paper. Experimental device about automatic control of a hydraulic press, in *Proceedings of Asian Simulation Conference/the 5th International Conference*, Proceedings of Asian Simulation Conference.

Sun, P., Grácio, J., Ferreira, J.A., 2005. Conference Paper. New experimental device of evaluating springback in sheet metal forming, in *Materials Science and Technology 2005 Conference*, Materials Science and Technology.

Sun, P., Grácio, J.J., Ferreira, J.A., 2006. Article. Control system of a mini hydraulic press for evaluating springback in sheet metal forming, in *Journal of Materials Processing Technology*, ELSEVIER.

Ferreira, J.A.[a], De Oliveira, J.E.[b], Costa, V.A.[a], 1999. Article. Modeling of hydraulic systems for hardware-in-the-loop simulation: a methodology proposal, in *Fluid Power Systems and Technology – 1999 (The ASME International Mechanical Engineering Congress and Exposition).* ASME.

Ferreira, J.A., De Almeida, F.G., Quintas, M.R., 2002, Article, Pages 237-248. Semi-emprirical model for a hydraulic servo-solenoid valve, in *Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, SAGE journals.