Hardware in the Loop Simulation-Based Training for Automated Manufacturing Systems Operators

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Abstract

Simulation-Based-Training (SBT) allows to train the operators of complex machinery within a safe virtual environment by means of effective lifelike learning experiences. SBT has been efficiently used in medical, aerospace and military fields and it may provide a competitive advantage also for the training of operators in mechatronic plants. In fact, at the current state of the art, human-machine interaction still heavily impacts on the final performances of automated plants. Since the fast-evolving process dynamics of the machinery is controlled and supervised by complex software logics, the main challenge for effective and valid SBT concerns the development of a real-time simulation, where the control system responsiveness is fully reproduced. This paper deals with a novel SBT workbench used for steel plants operator training, discussing the real-time simulation architecture developed for the purpose. Following a hybrid process simulation approach, real-time control Hardware-In-the-Loop technology assures seamless and accurate reproduction of the real plant, also achieving the desired Man-in-the-Loop practice for the operator interaction. A conceptual architecture for a virtual interactive prototype is proposed, including controllers and interfaces for trainer and trainees. A case study on an electric arc furnace is implemented within a Virtual Commissioning tool, analyzing its capabilities and limitations

1. Introduction

Flexible automation and intelligent manufacturing are based on reconfigurable and cognitive mechatronic systems capable to autonomously manage complex processes. However, the final productivity and the Overall Equipment Efficiency (OEE) still depend also on human operators supervision [1,2]. Efficient supervisory control through Human-Machine Interface (HMI) [3,4] requires correct interpretations of the process states and corrective actions, avoiding wrong input sequences that could result in performance degradations or even bad failures [5, 6]. It actually happens that different operators achieve different performances using the same plant. Therefore, the operators experience is fundamental to fully exploit the plant potentials. The supervision of the complex behaviours of automated manufacturing systems requires an expert interaction that can hardly be taught in a conventional way, since it often relies on experiences in multiple and unstructured scenarios. Training should then focus on developing skills through guided realistic life-like experiences and not just on acquiring information. Of course, training on the job is fundamental, but it is limited by time constraints, costs, hazard to trainees and to the equipment itself, especially in case of safety procedures. These drawbacks can be bypassed if training sessions are carried out in virtual environments [7]. Simulation-Based-Training (SBT) makes use of digital tools to realize virtual environments where the trainees are involved in realistic and interactive lifelike scenarios.

SBT has gradually become a useful technology in many fields, as e.g. medical, military, aerospace [8,9]. The virtual experiences involve hazards similar to a videogame and literature reports even performance improvements for training on simulated equipment as compared to training on the real ones. For instance, last generation flight simulators provide such a high fidelity and realism that they are certified to add credit hours for achieving or maintaining the pilot license. In general, however, each purpose has its own requirements and the main research areas are: i) physics and/or control simulators; ii) human-computer interaction and visual systems; iii) training session aids. Focusing the investigation on automated plant SBT, these challenges arise:

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- **realistic modeling** – the behaviour of the overall virtual plant relies on modeling products, processes and machineries. This involves the need for predictive modeling of the fast evolving dynamics and sequences, regulated by the control logics as executed in the controller. Then, the main challenge for effective and valid SBT is about developing a simulation where the interaction with the control system and the resulting process evolution are seamlessly reproduced;
- **cost effectiveness** – many SBT applications are too sophisticated and expensive to be adapted to each automated plant that is customized or even engineered to order. Then, the SBT material must exploit as much as possible any already existing engineering work, like CAD models and simulations;
- **user interaction** - operators interact with the HMI while keeping an eye contact with the plant. Therefore, an effective SBT on an automated plant cannot rely on the interaction with the HMIs only, but it needs 3D graphics reproducing the interactivity with the real working environment.

These considerations lead the present work in investigating the specifications for developing an automated plant SBT framework. The paper is organized as follows: Section 2 generally describes the virtual prototype for SBT purposes; a framework for reusing an existent 3D modeling package with HIL and its application on a validation case study are presented in Sections 3 and 4 respectively; Section 5 reports the case study results whereas Section 6 finally draws the conclusions.

2. Virtual Prototype for Simulation-Based-Training

SBT's foundation is a Virtual Prototype (VP) where the behavior of the automated plant and its view from the operators are reliably reproduced in real-time for a lifelike realistic experience. Such VP must respond to the inputs from the trainees actions as if it were the real automated plant. The interactivity is fundamental to virtually reproduce the lifelike experiences for training purposes, so that the VP should be based on a realistic digital model of the automated plant and reuse the real HMIs.

The virtual model should predict reliably the process behaviors providing at the same time a detailed graphics of the plant. A tradeoff between the computational weight of the CAD geometries and the behavioral models calculations with respect to the VP refresh rate should be achieved. The solution adopted is a Hardware–In–the Loop (HIL) hybrid process simulation approach [10] where the real controllers and HMIs are connected to a virtual model of the plant. The model size depends on the considered control level, increasing from process, machine, up to plant [11]. At process level the level of detail is higher and can reproduce the servo drives and structure frequencies, while the plant level mainly considers a discrete events model. The models must comply with the concepts of transparency and emulation, meaning that they must operate the whole IOs map so that the controller does not recognize any difference from the real equipment [10, 12]. The controllers interact at machine level with sensors, actuators, drives and other programmable devices, with an adequate but limited level of detail. The same considerations hold for the graphics, which must take into account only the stimuli perceivable by the operators. To that purpose it is convenient to export and reuse the 3D models in neutral formats from common CAD packages. Then, the geometries must be simplified saving computational weight by deleting useless information or parts. The process simulation is an exception and, if necessary, additional CAD models must be set up for its visualization and interaction with the plant. The traditional simulation models run with a predefined set of computation parameters, like specific initial conditions and finite test time, and the results are available for analysis only at the end of the test. On the contrary, SBT need a VP interacting with external agents with unpredictable behavior rather than just a predictive numerical computation. This is a continuous cycle execution without predefined temporal limitations. The VP then runs through start, all nominal, auxiliary and degraded scenarios, transitions between them, stop. All the simulation models must be synchronized to reproduce and emulate the real behaviors. Due to the heavy weight of the numerical computations, the engineering simulations generally run in virtual time, where the time is represented by a variable while the events flow waits for the calculations. All the models of a simulation are then synchronized with the same explicit time variable. The simulation solver must wait for the end of the last model cycle to update the time variable and to start the computation again. Due to the evolution of the models, which may call additional algorithms or not, the cycles computations vary and the time updates cannot guarantee a constant time flow. This Virtual Time flow depends on the computation durations and synchronizes the interaction of the virtual models. If the simulation models must interact with the control HIL, also the external hardware clock might be slowed down to have the same synchronization.

This is possible only in case of advanced controllers, and not for most common PLCs, as far as the authors experienced. In fact, the controller tasks are executed in real time, which means they follow the time of the real physical world, as ruled by the clock, and they are also subjected by time diagnostics. This same run mode can be generally declined into hard, firm or soft real-time, depending on the consequences involved in missing a deadline. In order to be HIL interfaced with the controller, a model for SBT must be executed in hard real-time.

3. AUTOMATED MANUFACTURING SYSTEMS VIRTUAL PROTOTYPE MODELING

The structure of the VP for SBT is presented in Fig. 1, the dashed boxes represent the areas interested by controller HIL and Man-In-the-Loop interactions. The actual controller executes the control logics exactly as reused from past plants and reconfigured with additional functions. The control logics use the VP sensor variables and the HMIs signals as Inputs, computing its Outputs commands to the same VP and HMIs. The virtual behavior of the plant processes its variables according to its own internal state and to the controller Outputs read from the HIL interface. The virtual behavior feedbacks the sensor variables to the controller Inputs and manages the 3D CAD with special functions. If the CAD mathematical model should influence the VP behavior or it should be used just as a graphical interface is still a topic of discussion [10]. The CAD can natively embed data, e.g. for collision and dynamics, but its update computation in hard real-time would fail the real-time diagnostics. Then it is easier to maintain the 3D CAD representation separated from the plant behavior model and updated in soft real-time with quite longer and independent cycle times. The trainee interacts with the real HMI while keeping eye contact with the 3D CAD representation. Consequently, he is able to take decisions and to act on the controller Inputs through the HMI. In parallel, the trainer guides the activities with additional information from another HMI. This can be even set up with a virtual panel in the same VC software, but hidden to the operator, for instance in a second screen. The trainer actions can also bypass the virtual behavior results to force transitions between plant states.

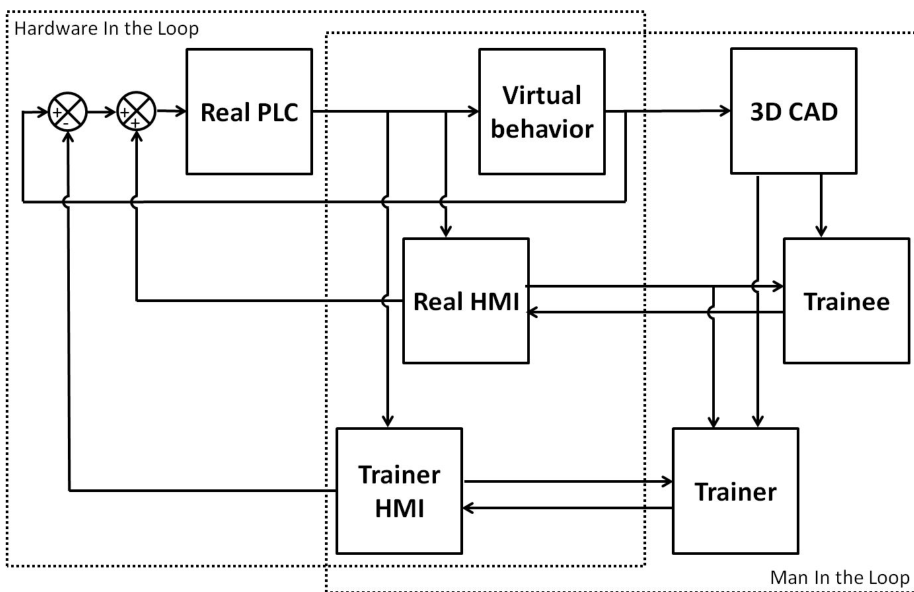

Figure 1. Schematic of the modeling framework for the Virtual Prototype.

4. CASE STUDY

The modeling of the VP of an Electric Arc Furnace (EAF) served as validation case study on SBT. The real EAF is a powerful furnace that melts steel scraps by an electric arc. The evaluated EAF weights about 1.000tons, with a production throughput of about 100tons/h, an operation cycle duration of 1h, a molten steel temperature >1600°C, 90MW of power and 60.000A of alternating current through three ϕ400xL6500mm graphite electrodes. The real EAF has a high level of automation and clearly involves hazards and very high fixed and variable costs. Complex control logics embed models that optimize the process parameters but expert operators are needed for high level supervision. The operator training requires long times and cannot reproduce many incipient critical scenarios.

The VP graphical model is shown in Fig. 2. The EAF is controlled by two Siemens SIMATIC S7-400 PLCs. The first PLC controls the process by analyzing the AC waves and accordingly adjusting the working parameters. The second PLC supervises the EAF functions controlled through the HMIs, like scraps charging, slagging, liquid steel tapping, robot temperature and chemical sampling and ladle car leaving. The operator works through the HMIs from a control pulpit, shown in Fig. 3.

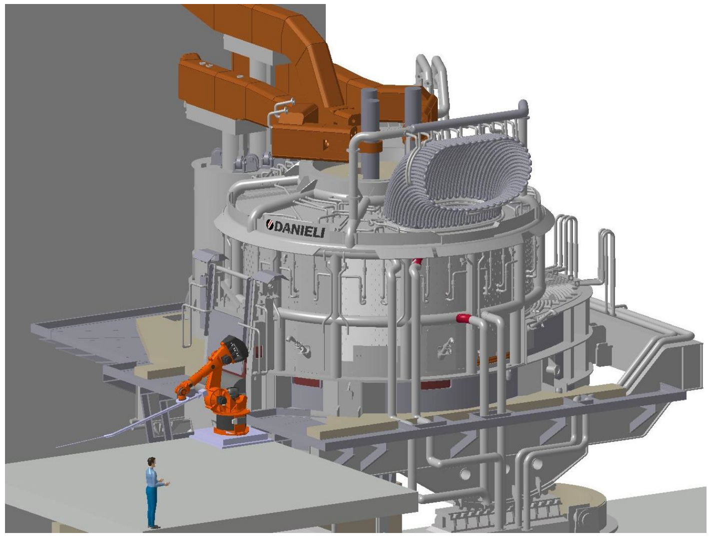

Figure 2. Virtual Protototype of the EAF (*courtesy of Danieli Automation*).

Figure 3. Real operator control pulpit, (*courtesy of Danieli Automation*).

4.1. BUILDING THE VIRTUAL PROTOTYPE

The VP development exploits the features of the virtual commissioning tool Delmia Automation, from Dassault Systèmes. First, a realistic representation is achieved by importing neutral *.step files exported from Autodesk Inventor CAD 3D software. The CAD assemblies are simplified for reducing the computational weight of the representation. Then the nominal behavior of the system modules is set up, emulating the necessary IOs to/from the controller [13]. The system is divided in simulation modules: mechanical, actuators and electrical devices and processes. Mechanical devices are linkages, dynamic behaviors if necessary, logic interactions and collisions. The actuators are electric motors, hydraulic cylinders and a robot. Electrical devices are the electrodes. The considered processes are steel scraps handling, melting, liquid roll and flows. The sensors are not mentioned as simulation modules since they are just variables from other modules, but made global in the VP as ports. The modules behaviors are modeled with IEC 61131-3 programming languages. Finite state behaviors use Sequential Function Chart (SFC) for sequential and parallel operations. Dynamic, continuous and logic behaviors are set up with Function Block Diagram (FBD). The models use internal variables to keep their state and external ports to communicate outside. The ports are just global variables, but named differently (such as M_*, E_* and L_*) to describe, respectively, mechanical, electrical or logic parameters. Special functions link the model variables to the CAD models and to the simulation timeline. The representation is completed with additional CAD models and advanced mechatronic behaviors, such as the process simulation in Fig. 4 and the graphic effects as stimuli to the operator. More complex but stateless mathematical functions are finally written in C++.

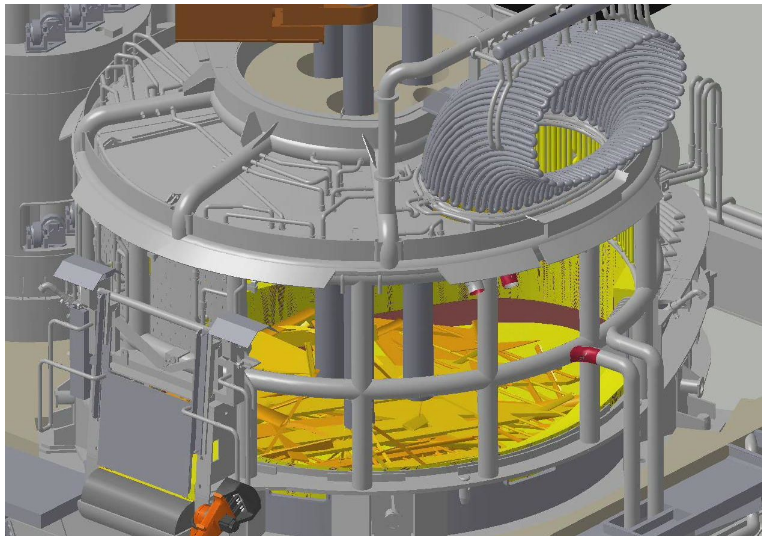

Figure 4. Representation of steel melting in the EAF, (*courtesy of Danieli Automation*).

4.2. HARDWARE IN THE LOOP INTERFACE

To evaluate the control of the VP of the EAF there are two options: the control logics can be imported in a controller emulator in the virtual environment, otherwise they can be run on the real PLCs and HMIs. The case study follows the latter method to provide a realistic experience by reusing the real HMIs and to save the work in porting the source code and verifying the controller emulator. The PLCs are so HIL interfaced with the simulated EAF through Siemens OPC-Scout, an OLE for Process Control server. The software and the VP are completed with specific data blocks for reading and writing the signals, replacing the real cabling to peripherals slaves. The operator HMIs are directly connected to the PLCs, as in the real system.

The VP model, the PLC and the OPC server have all some limitations. The model execution is not in real-time but in virtual time, due to the computational weight for the synchronization of behavior models and CAD representation. On the contrary, the PLC is hard real-time, with no possibility to change to a virtual clock. Finally, the cycle time of the OPC communication is slow, about 0.1*s*, with a negligible jitter. The first tested solution runs a clock into the PLC, as a watchdog, and parameterizes the virtual model integrators with sampled PLC time intervals, completely bypassing the simulation time. This results in too slow updates at about 8-10Hz, which are perceived as jerky motions by the trainee. The final solution is the algorithm reported in Fig. 5. The algorithm monitors the PLC time, "*PLC.time*", and accordingly synchronizes the simulation time, "*SIM.time*", considering the error, "*Error"*. Then, smaller simulation steps, "*SIM.time.step*", are advanced for a smooth running. The simulation steps are hypothesized from the previous duration between two communication, "*PLC.time.step*", and the number of simulation steps, "*SIM.steps*", occurred in the meanwhile. The steps are advanced till the simulation time arrives at the expected new PLC one. When a new communication occurs the routine starts again from correcting little timing errors.

The presented synchronization algorithm achieves the needed trainee interactivity, but does not solve completely the real-time issues. In particular, the consistency controls fail due to the IOs update in this too slow cycle time. The ready and easiest solution is the control engineering practice to conveniently short circuit the IOs to comply with the software emergencies, so as to partially run the other software functions.

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Algorithm Synchronizer
Input: PLC.time – PLC clock; SIM.time – synchronized simulation time flow;
       Inputs – Inputs from PLC and HMI
Output: SIM.time.step – time step for the numerical integration steps;
       Outputs – The simulation outputs
Init variables
Model run
if PLC.time>pre PLC.time then
  | Error=PLC.time-SIM.time   /*synchronization error between PLC.time and
  |                              SIM.time*/
  | PLC.time.step=PLC.time–pre.PLC.time+Error   /*time between previous and
  |                                                actual OPC communications*/
  | SIM.time.step=PLC.time.step/SIM.steps
  | SIM.steps=0
  | pre.PLC.time=PLC.time
  | while SIM.time<pre.PLC.time+PLC.time.step do
  |  | Outputs=f(Inputs,State,SIM.time.step)   /*VP model execution*/
  |  | SIM.time=SIM.time+SIM.time.step
  |  | SIM.steps=SIM.steps+1   /*number of integration steps between two OPC
  |  |                            communications*/
```

Figure 5. The algorithm that synchronizes simulation and PLC.

5. Case Study Deployment and Results

The potential of VPs for SBT is well exploited introducing special visualization features to aid the trainee in the error identification and explanation. For instance, some parts of the present CAD model change their color when they collide or other failures happen, like excessive temperature or pressure in air and oil pipes and vessels. Some models change from visible to hidden to aid the trainee to better learn how to manage the EAF. For example, during critical ramp up the furnace walls become transparent to show the melting process evolution, as shown in Fig. 4. The process realistic visualization show the operator how the operations progress. To that purpose the processed materials, shown in Fig. 6, change in shape, dimensions and colors, better visualizing the process deployment as function of operating parameters like electrodes positions and power with respect to the material.

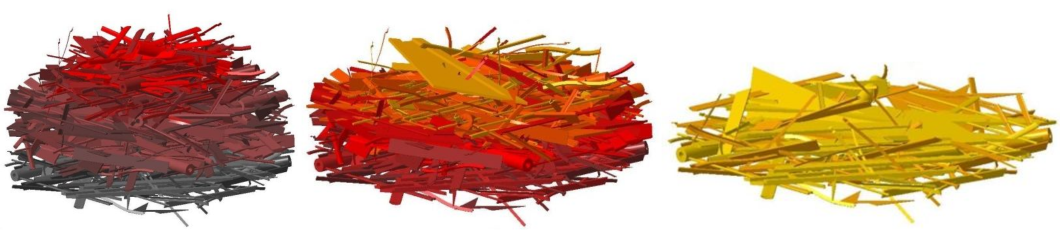

Figure 6. CAD model for steel scraps melting.

The trainee can also interact with the CAD models via special functions that activate Boolean signals in the simulation if specific parts are selected through the computer mouse. The signals are used to purposely change colors or even parts hide/show or to transition into different scenarios. To enhance the SBT effectiveness, a secondary trainer HMI was developed. With such HMI it is possible to introduce failures or to change operating scenario, challenging the trainee with un-forecasted situations. Special CAD views are automatically setup during different training scenarios and eventually under the direct input of the trainer.

The EAF operator SBT is shown in Fig. 7, where the real EAF pulpit is enhanced with a view on the VP, controlled by the HIL PLCs, HMIs and additional equipment. Different HMIs possibilities are introduced with alternative command sequences and nested menus. First, best practices and patterns are recorded from experienced operators interacting with the VP. Then, new operators are trained on the procedures, evaluating the time needed to identify the scenarios and to implement the corrective actions. The interactive simulation uses all but only the PLCs IOs, without any bias behavior from work habits. Thus, the VP reliably responds to correct or even dangerous commands. Finally, the evaluations on the virtual experiences are collected from interviews to trainers, trainees and experienced operators and give important feedbacks on the features for MIL interactions with the VP. The interaction between the trainee and the VP through the HMI reproduces the reality as far as useful, providing the necessary stimuli for SBT on the operations with cost effectiveness. The view on a 3D representation of the EAF from a control pulpit is sufficient for this training application, since it reproduces the real operator work. The interaction with the 3D models goes beyond the teaching of information, including a greater awareness of the evolution of the system in state space.

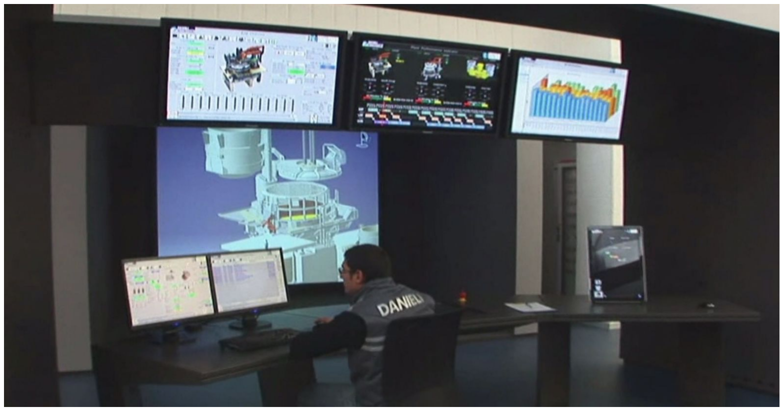

Figure 7. Operator experiencing the virtual prototype from the control pulpit, (*courtesy of Danieli Automation*).

One of the main advantages achieved with this SBT solution is the extensive reuse of existing engineering data and software tools. The SBT material was quickly setup reusing Autodesk Inventor 3D CAD models and Siemens S7 controllers into Dassault Systèmes Delmia Automation tool for Virtual Commissioning with reduced costs and development time. Furthermore, SBT was also integrated into the plant development process and used as a collaborative, Man-In-the-Loop, design tool to explore human factors on final manufacturing system performances. A well appreciated SBT feature is the possibility to train the operator on critical situations, like virtual hazards, without any real damages to humans or equipment. The knowledge is delivered through training sessions focused on specific scenarios that can be quickly reached without waiting for the whole manufacturing sequence from the beginning. This means that the operations can be iterated until to the goals are reached, saving time and resources with respect to the real plant. Also, the training can follow specific sequences different from the real plant ones, but just depending on the training purposes.

6. Conclusions and Future Works

The present paper reports the specifications for adapting existing engineering tools for the industrial introduction of the SBT of the operators. The experience interactivity for trainees and trainers, real-time and details level demands are fundamental, but must focus just on the operator skills to be trained. The strength of the adopted approach is the capability to reuse existing engineering material and tools and to set up hybrid VPs with control HIL in a system perspective. A large case study on a powerful EAF has been used in order to evaluate this SBT method feasibility and exploit the existing engineering work. Additional features were developed to allow the design of new training sessions. A control HIL simulation enables a predictive and reliable reproduction of real life experience. The resources required to set up the training material resulted sustainable. The VP enables new training strategies above the conventional training due to new possibilities of interaction with the plant, including information not reachable in the real manufacturing system due to safety control or other physics constraints. Other advantages are lower costs, easier logistics and safety for the courses. With the SBT, the operator training can be carried out concurrently with the system final development stages, up to the real commissioning, to shorten the rump up time. The OPC communication, even if simple and easy to implement, showed important drawbacks in terms of refresh rate, then future works will explore faster HIL communication solutions. SBT is addressed to operators of automated manufacturing systems but showed to be effective even for design engineers and sales agents.

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