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Virtual Commissioning with a Model-Driven Digital Twin

In the manufacturing and automation industry, adopting new development techniques has become a key requirement for success in a highly-evolving, competitive market. As demands on product requirements increase, the inherent design risks can pose significant problems, threatening the success and reputation of those trying to keep pace. To mitigate this risk, the technique of virtual commissioning (VC) promises to reduce the significant delays and costs associated with the difficult task of system integration and commissioning. While previously only possible by a few niche experts, powerful modeling tools and compatible information standards have paved the way for modern, accessible virtual commissioning solutions.

The Evolution of Virtual Commissioning

Since its inception, the intention of virtual commissioning (VC) has been to help solve a variety of problems that can arise when manufacturing systems are brought together for integration and operation with a programmable logic controller (PLC). The automation industry has long acknowledged the potential benefits of using virtual models to simulate the performance of physical systems, where integration issues could be spotted before entering into the expensive process of physical integration. For a successful VC, however, the virtual plant model must be an accurate representation of the system in question, and while these kinds of models had some prominence in the aerospace and automotive industry, their implementation was lacking in the automation market. To achieve implementation, companies needed plant models that could be integrated with their PLC design methods – something unavailable by the early standards of plant modeling.

As early as 1999, researchers were hard at work trying to define and propose VC strategies (Auinger et al. 1999) that could realize these expected benefits. A technique called “soft-commissioning” was described that could pair simulation tools with hardware PLCs, and help debug a portion of the expected behavior of the physical system. Although the technology was still severely lacking, the researchers were able to demonstrate success. Since that time, VC development has been organized into four categories of general control development (Auinger et al. 1999):

- **Traditional Commissioning** involves testing the physical system (plant) against the hardware controllers without the assistance of virtual modeling techniques.
- **Soft Commissioning** (or **Hardware-in-the-Loop (HIL)** testing), employs a virtual plant model that is used to test the hardware controllers.
- **Reality-in-the-Loop**, alternatively, tests simulated hardware controllers against a constructed, physical system.
- **Virtual Commissioning** is the process of testing that uses both a virtual plant model and a virtual control system for simulation.

Each of these four strategies requires different technologies in order to be successful. By 2010, researchers were still working on improved ways to facilitate a user-friendly approach to the VC process (Hoffmann et al. 2010). They described the major challenges as 1) the easy creation of sufficient plant models, and 2) the ability for these plant models to work in tandem with PLC development software. In light of these challenges, practical implementation of VC techniques was deemed out of reach by the standards of 2010.

Despite these challenges, technologies have now been developed that make VC implementation possible for the majority of automation companies. As far back as 2006, it was demonstrated that VC techniques stood to save up to 75% of the time required for traditional commissioning when studying German machine tool builders (Zah et al. 2005). Today, new technologies and software integrations are significantly reducing the historical barriers associated with virtual commissioning.

Technologies for Virtual Commissioning

For virtual commissioning to be a practical technology for the manufacturing and automation industry, the creation and function of virtual plant models needs to be sufficient for their usage outside of niche experts or simplified demonstrations. The development of advanced, model-driven design practices has taken form in what the automation industry is now referring to as a digital twin, which refers to the virtual plant models in question while differentiating itself from the historical, typically simpler models that were unable to function as fully as their modern counterparts. In addition to these digital twins, the software standards for model connectivity have also seen drastic improvements. Together, these technologies are permitting the widespread practicality of VC throughout the automation industry.

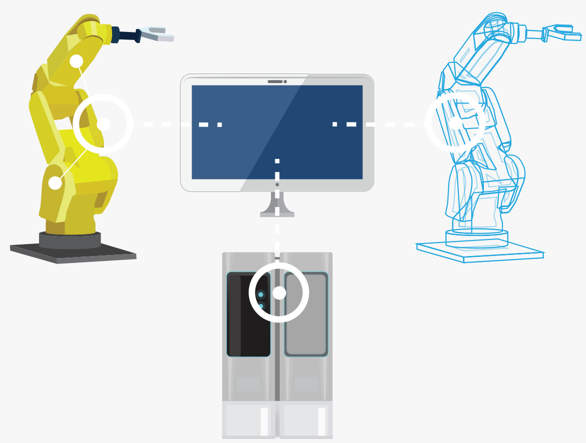

Figure 1: With the advent of digital twins and common integration standards, virtual models can connect with virtual control code, PLC hardware, and even the physical product itself.

Model-Driven Digital Twins

A digital twin is a dynamic, virtual representation of a corresponding physical product. These models can range widely in their purpose and fidelity, but they serve as a powerful connection to the product for diagnostics, design changes, and the VC process. Companies are increasingly using digital twins to optimize their products in ways that were previously either unrealistic or impossible.

With system-level modeling tools like MapleSim, the creation of a model-driven digital twin can begin alongside the design process. While past attempts at virtual commissioning employed the use of model-based techniques, they lacked the fidelity and flexibility required to make the process feasible for common usage. Now, modeling tools allow engineers to begin their process by importing their CAD information from other tools. The CAD import technology has become an important development to make digital twins more accessible to the automation market. Model-driven digital twins are now an important, emerging trend in the automation industry, making VC more accessible and adding a variety of other capabilities to other parts of the design process.

Functional Mock-Up Interface

A challenge that had to be overcome before VC could really take off was how to seamlessly connect the required models together. The complex physics of a given plant model were typically simulated using a platform that operated differently than the logic-based systems of PLC design. In 2010, the Functional Mock-up Interface (FMI) was developed as a standard interface for a variety of model-based processes.

The FMI standard is a collection of all the necessary information for a given model, organized in a way that allows for import and export with a variety of software tools. It is defined as single, archive-based file containing variable definitions, a full set of system equations in C code or a compiled library, and all other parameters relevant to the particular model. In some ways, the FMI standard bears resemblance to a Simulink® S-Function, which is another common technology for integrating model-based tools. FMI was, in part, developed to overcome the proprietary nature of S-Functions, and to be easier to integrate for simulation tools that require a simpler, tool-independent standard. Subsequently, FMI has gained increasing adoption, and, as of 2017, it is supported by over 40 common engineering tools. With this tool support, FMI is now a key technology for exporting model-based digital twins to the PLC control software for a more integrated test platform.

The Virtual Commissioning Workflow

With the right tools in place, it is now possible for many organizations to adopt VC techniques for their machine design projects. They may use VC in order to reduce their overall commissioning time, to reduce commissioning costs, or to create a more reliable time to market for reputation purposes. While the applications and specifics can vary greatly, a typical VC process has many commonalities.

Construct the Model-Based Digital Twin

To begin, a model-based digital twin is constructed using a system-level modeling tool. Using these tools, the virtual model is developed either from existing CAD information, or from design concepts that are realized using the tool's component libraries. In this workflow, the system-level modeling tool, MapleSim, is used to demonstrate the process of starting from CAD models. Developed by Maplesoft, this tool allows for automatic CAD import so the digital twin can start with validated geometries of the design concept. Without previous CAD models, engineers can begin by using drag-and-drop components that can be customized to their specific designs, but this process typically requires more time and effort than CAD import.

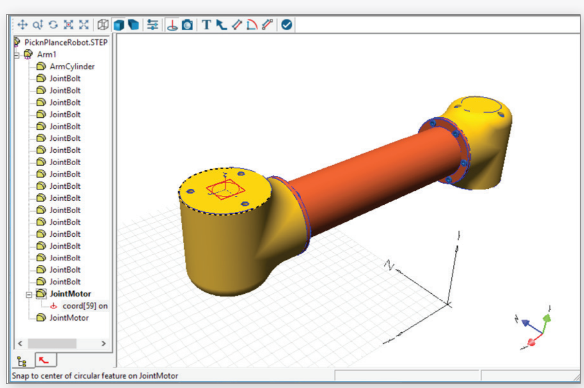

Figure 2: The automatic CAD import in MapleSim.

The CAD information is brought into MapleSim, where it is categorized into rigid bodies and frames with corresponding center of masses, among other parameters. These bodies generate individual component blocks that can be used in conjunction with all other standard and custom components required during model creation. The amount of fidelity required for a digital twin is fully dependent on the requirements for simulation. A higher fidelity model requires more effort to create, but can answer increasingly specific design questions, and offer a more realistic representation of performance for PLC validation. In the past, higher fidelity models were either too difficult to create, or simply couldn't be used when hardware validation required real-time simulation performance. Software tools like MapleSim are designed specifically to produce simulation code that is optimized for simulation speed, allowing high fidelity digital twins that can be useful for a variety of VC requirements.

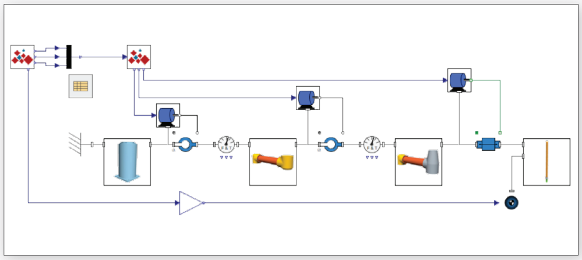

Figure 3: The system-level model, using component blocks from the CAD model.

Actuate and Analyze the Digital Twin

Before connecting the digital twin to automation software, the simulation software tool is used further to investigate the model and, optionally, perform a variety of design analyses for functional verification of the plant model itself.

The validated mechanism, now in MapleSim, can be actuated in a variety of ways, depending on what data is available to the engineer. Using standard MapleSim components, such as servo motors, the actuation can be defined for each joint, specific to the particular motors and requirements of the design concept. Users also have the option to define actuation by importing external libraries of actuators, or by using empirical data from specific motors. Model inputs are defined by parameterizing the system for the specific requirements of the VC process, which is a common task accomplished with parameter tables available using the simulation tool. Motion paths and loading are defined in conjunction with design requirements, using the inverse kinematic equations that are available through MapleSim's analysis features. These details form an important part of defining the inputs to the model, which are maintained when the model is exported as a Functional Mock-up Unit (FMU).

Lastly, the model outputs are defined as a collection of sensors and probes according to design requirements. Using a system-level modeling tool like MapleSim allows the engineer to specify outputs for any variable of system performance, which is carried into the FMU for access by the automation software.

Integration with Automation Software

When the digital twin is created, it can be exported by MapleSim as an FMU, which includes all of the necessary information for usage by the automation tool. The FMU includes optimized C code that specifies the set of differential, algebraic, and discrete equations that describe the behavior of the physical system. The FMU standard is supported by an increasing amount of automation tools, such as B&R Automation Studio. Using an automation tool, the engineer will import the FMU, and will then have access to the model's inputs and outputs, in order to define their connection with the virtual PLC code.

At this point, both the virtual model and the virtual PLC code reside within the same environment. While testing can begin, it is also possible to use PLC code that is designed with the digital twin model in the controller logic itself. If the digital twin is of a sufficient level of fidelity, and validated for accuracy, the engineer might forego the requirement for specific physical sensors on the final product, and instead instruct their PLC code to call for specific information from the digital twin instead. This technique is an emerging method to reduce the costs associated with installing expensive physical sensors on a machine, since the digital twin is able to simulate the system in real-time, offering the same information that a physical sensor might.

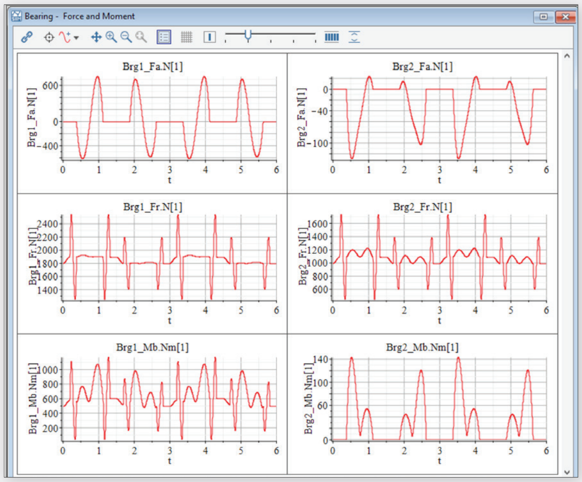

Figure 4: Analysis performed on the model within MapleSim, showing bearing forces and moments at various locations on the mechanism.

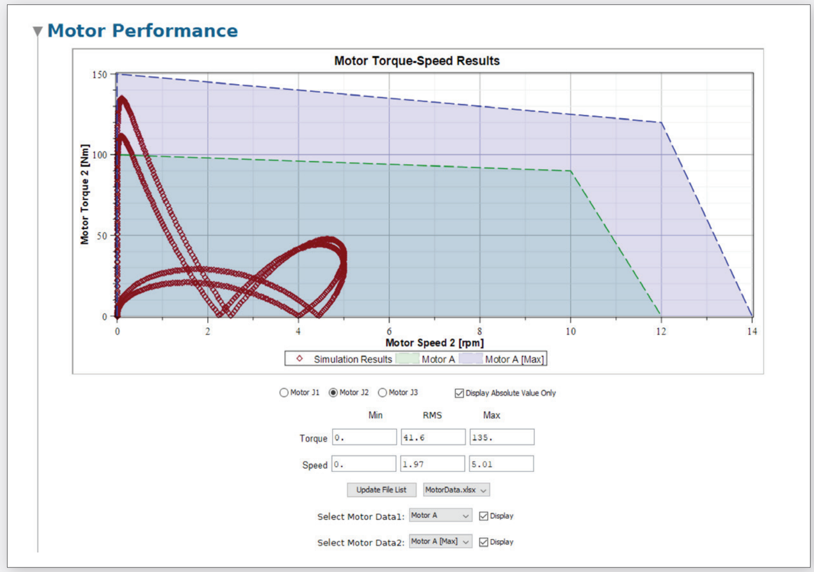

Figure 5: Motor sizing analysis on the virtual model can be performed using custom applications to ensure proper performance and reduce over-engineering.

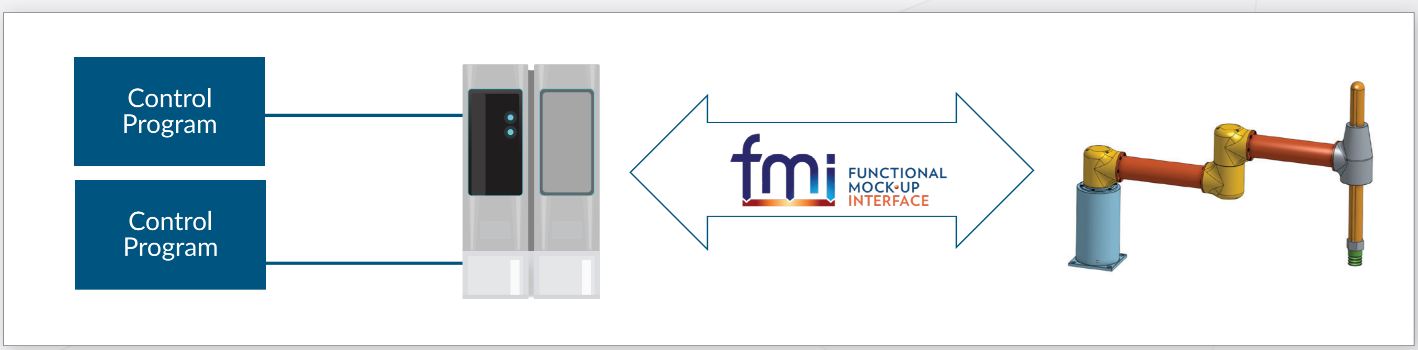

Figure 6: The Functional Mock-up Interface serves as the connectivity standard for connecting digital twins to PLC programs.

Virtual Commissioning Techniques

The automation software, with all of the required information now centralized within it, is able to perform a variety of VC tasks that would otherwise have waited until the physical commissioning process. Because both the plant model and PLC code are in a virtual environment, simulations can be performed on a large scale, allowing for iterations that test the performance of the PLC code in various scenarios. Engineers will look for bugs in control code that may cause slowdowns, performance issues, safety concerns, or other results that would compromise the functioning of the physical system. When performance issues are discovered, they can be diagnosed with a transparency that is difficult to obtain during a physical commissioning process. By either inspecting the PLC code, or the plant model itself, the source of the issue can be debugged using the range of model information available. In a physical commissioning process, the engineer may have difficulty isolating the performance issue, as the full range of parameter and variables in the plant model are not nearly as accessible for diagnostics.

Another technique employed in this stage is to replace the virtual PLC code with the PLC hardware itself, and connect it to the input and output signals of the digital twin. Due to the requirements for real-time simulation, this task was previously inaccessible for many situations that required a high fidelity model for useful results. With optimized FMUs available from modern tools like MapleSim, engineers can test the physical controller hardware against the virtual model, providing another technique to debug issues before proceeding to construct the physical system.

While neither of these techniques will completely eliminate the risk involved in the physical commissioning process, they can serve as resource-efficient techniques to isolate issues much earlier in the design process. Virtual commissioning is also differentiated from physical commissioning in that it can be run as a concurrent process alongside many other tasks in a design project. Because testing can begin while both the plant and controller are in a virtual state, the relative cost of design iterations is minimal, allowing engineers to perform VC at an initial, high-level view, and to continue returning to VC as the design is refined and testing needs are further specified.

Using Digital Twins beyond Virtual Commissioning

Virtual commissioning is a major technological development in the automation industry, and the use of a model-driven digital twin is central to the accuracy and success of this technique. However, in addition to VC, there are a variety of other ways that a digital twin can improve the design and operation of a product.

- **Conceptual Development:** Very early experimentation with design concepts in a model that predicts the dynamic behavior of the design provides powerful insight and allows engineers to make more informed design decisions.

- **Online Diagnostics:** Running the model performance of the digital twin in parallel with the real machine can provide valuable insight into where a problem might arise as the machine's response drifts from the model as it ages.

- **Virtual Sensors:** Since the dynamic response of the digital twin is built on rigorous physical laws, certain internal calculated properties may be sufficient to use as inputs to the control system, either to temporarily replace a faulty sensor until it can be fixed, or eliminate the use of that sensor altogether. Both scenarios can provide significant reduction in costs.

- **Predictive Maintenance:** There are many factors that determine the maintenance schedule for a machine, but one factor is frequently overlooked because it is difficult to predict without a digital twin. This factor is the impact of dynamic loading on bearings, gears, and motors, caused by changes in the duty cycle. Putting a digital twin through a proposed duty cycle can help to determine the loads on these components and the impact on the component life.

- **Product Enrichment:** All the above operations most likely take place on the real-time automation platform or SCADA system by engineers in the design office or operations room. However, we are already seeing several manufacturers moving this capability onto the machine itself, so these capabilities can be offered to the operator on the shop floor. These valuable features will allow manufacturers to provide greater innovations and differentiate themselves from their competition.

- **Sales Tool:** Outside of the engineering department, the digital twin can be used in the selling process to qualify customer specifications and provide accurate information that is specialized to each customer. This information can help validate the performance and operation of a machine given different payloads or operating conditions, without needing a full consultation by the engineer.

Going Forward

Since the advent of virtual commissioning, many technological barriers have been overcome in order to realize the benefits of model-based system integration. The current state of technology can offer practical VC techniques that are more accessible than ever to the manufacturing and automation industry. As part of a growing need to speed development and minimize the inherent risk in developing new, innovative products, digital twins and virtual commissioning techniques are quickly becoming essential technologies. The technology and standards behind virtual commissioning are currently being heavily invested in by companies and research groups around the world, creating easier, more powerful techniques for model-based design. As these technologies continue to develop, their role in the automation industry will continue to grow into an essential component of modern, high-performance product design.

References

Auinger, F., Vorderwinkler, M. and Buchtela, G. 1999. "Interface driven domain-independent modeling architecture for 'soft-commissioning' and 'reality in the loop'", Proceedings of the 1999 Winter Simulation Conference, Phoenix, AZ, USA, 1, pp. 798-805.

Hoffmann, Peter & Schumann, Reimar & Maksoud, Talal & Premier, Giuliano. (2010). Virtual Commissioning Of Manufacturing Systems - A Review And New Approaches For Simplification. Proceedings - 24th European Conference on Modelling and Simulation, ECMS 2010. 175-181. 10.7148/2010-0175-0181.

Hoyer, M., Schumann, R., Hoffmann, P. and Premier, G. C. 2008. "Virtuelle Inbetriebnahme mit ModelCAT - Vom Prototypen zum industriellen Einsatz / Virtual Start-Up with ModelCAT - From Prototypical Realisation to Industrial Implementation", Automation 2008, BadenBaden, VDI-Berichte 2032, pp. 203-206

Zäh, M. F. and Wünsch, G. 2005. "Schnelle Inbetriebnahme von Produktionssystemen", wt Werkstattstechnik online, 95, 9, pp. 699-704

Figure 7: Digital twin technology is playing a central role in Industry 4.0 trends, offering the ability to provide insight, diagnostics, and control for product operation.

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