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Added value from virtual sensors

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Abstract

Developments in simulation techniques and algorithms combined with increased computational capacity has made it possible to simulate the dynamic behavior of complex machinery with a high degree of accuracy even in real time. In this chapter, the concept of the virtual sensor is explained: first on a general level, and then in more detail and by introducing a few case studies deploying different simulation tools. Combining actual measurements and the simulation model enables the use of simulation methods to estimate the dynamic behaviors of a machine in situations where measurements are not possible or economically feasible. There are two main categories of virtual sensors. The first, suitable for low complexity cases, is based on analytical models. The second is based on detailed numerical models. It is suitable for more complex cases. Sensor measurement can be further divided into online and offline measurements, the difference relating to measurement pace. From the business perspective, the virtual sensor can potentially provide better insight into a machine and its operation, and therefore bring added value that original equipment manufacturers can offer to end users. Moreover, virtual sensors can lead to a reduction in the number of physical sensors needed, thereby reducing cost.

Keywords: Virtual sensor, soft sensor, simulation, digital twin, cyber-physical system

8.1 Introduction

The chapter introduces the concept of virtual sensors in the context of simulation and explains how they can add value for original equipment manufacturers (OEMs), end-users, and other stakeholders in the value chain. The concept of virtual sensors is known to some extent by engineers working in research and development (R&D), and virtual sensors are applied in the R&D phases of new equipment development. However, their potential to provide valuable insights for other facets of business operations such as the maintenance and repair businesses and other after-sales services is currently undervalued and unexploited.

This book introduces different aspects of digital tool use for different phases in the value chain for machinery manufacturing and sales. Virtual sensors are one of the tools in the digital toolset. Whereas the book introduces different opportunities for simulation methods on a general level, this chapter gives an overview of a specific method for using a physics-based digital system model seasoned with actual measured data.

The objective of this chapter is to introduce the concept of the virtual sensor. The concept is simple, but its implementation for machinery requires understanding the limitations introduced by the methods used to build the models that are deployed by virtual sensors. In addition, to better understand the accuracies and the practical limitations of the introduced methodology, it is important to understand what kind of data can be captured from existing systems and used as input for the simulation models.

The importance of the chapter topic arises from the fact that not every behavior of a complex physical system can be economically measured or measured at all, because geometry limitations or environmental conditions can hinder or prevent access. Instead of taking measurements using physical sensors, a physics-based digital twin makes it possible to use digital methods to gain virtual access to the system of interest. Understanding the novel business opportunities and added value made available by taking a virtual approach can directly lower end-product costs and give additional insights about the machine. These additional insights can help, for example, to estimate machine risk in detail, and therefore lead to an increase in after-sales services as discussed in Zheng *et al.* (2018).

The chapter is structured as follows. First, the concept of virtual sensors is introduced. The introduction includes the general overview of virtual sensors explaining the challenges of using the hardware sensors for which the virtual sensors are providing a cost-effective alternative. The chapter also discusses the capabilities of the virtual models on a general level, focusing on their capabilities to conduct virtual measurements of the behaviors in physical systems. The limitations of the technology are introduced and discussed on a detailed level to clarify both capabilities and limitations. At the end of the chapter, business opportunities introduced by virtual sensors are discussed in general. Finally, recommendations are introduced for different stakeholders including business managers and entrepreneurs, academia, educational institutions, and policy makers.

8.2 Virtual sensors: Context and background

Digital twins belong to the group of cyber-physical systems (CPS), where the integration of a cyber world and the dynamic physical world are represented. In general, a CPS is divided into two parts: the digital twin, a virtual counterpart of the physical system, and the actual physical system including its hardware sensors and connection to the control system. The machine system includes the control system and hardware sensors whether or not the machine is human operated or automated (*e.g.*, a programmed process without human interaction). The digital twin is directed towards engineering aspects, whereas the virtual models and data are the primary focus (Tao *et al*., 2019).

Usage of the term “digital twin” increased rapidly after its definition by NASA in 2010 (Shafto *et al*., 2010), although the term had been defined earlier in 2002 (Grieves M., 2005). According to NASA, the digital twin is a method of predicting the structural behavior of an aircraft by simulating and analyzing its behavior via its digital model. Since then, the term has evolved to include more aspects and other general approaches including Industry 4.0, machine learning, wireless communication, and cloud computing (Negri *et al*., 2017). The definition of term “digital twin” and its evolution can be found from the review of Negri *et al*. (2017). The benefits of these systems originate from ideally having all parts connected in real time, allowing them to operate based on each other’s data (Al-Ali *et al*., 2018).

In 2019, the definition of digital twins expanded, and the concept now applies to the product it represents throughout its lifecycle, *i.e.*, from design to manufacturing and operation (Lu *et al*., 2020). Today, the term “digital twin” covers so many aspects that comparison of various implementations has become difficult. This has resulted in the need to evaluate and compare digital twins by metrics (Autiosalo *et al*., 2019) and to introduce categorization based on the sophistication/maturity level of each (Madni *et al*., 2019).

In this book, the digital twin is presented in the context of its physics basis and featuring its real-time capabilities. The physics-based digital twin uses the laws of physics as boundary conditions resulting in virtual models that can accurately imitate the behaviors of real machinery. Physics-based real-time simulation models have been used widely for mobile working machinery. For example, see the excavator model in Alaei *et al*. (2019), the agricultural tractor model in Jaiswal *et al*. (2019), and the forklift model in Khadim *et al*. (2018). In addition, the real-time capability of digital twinning makes it possible to run the simulation model in parallel with the actual machine. That is to say, the model can replicate machine maneuvers as the machine carries them out. The virtual sensor is one tool in the digital-twin toolset that can be used to improve machine operation by giving the operator a better understanding of the machines’ dynamic behaviors. In the product development process and later in the product lifecycle, condition monitoring and fault diagnostics provided by digital twinning are promising features that can be exploited to improve the performance of machinery (Negri *et al*., 2017).

Real-time simulation can give the operator an experience similar to that of actual machine operation. In addition, it makes it possible to study, in real time, how different parameter settings will affect the machine’s dynamic behaviors. It also enables timely analysis of the machine’s condition during or after fault events. Simulation tools offer the possibility of studying systems in real time using computationally efficient simulation methods. At the cost of accuracy, some of the deployed methods provide computational efficiency by employing a simplified methodology. However, the most advanced simulation methods, such as multibody dynamics simulation, are capable of simulating behaviors in real time with rather complex models and high accuracy. Additionally, the real-time simulation models can run in parallel with the actual machine making it possible to provide real-time information from the virtual sensor readings to be used for predicting machine condition and assisting in decision making during controlled maneuvers.

A simulation model that takes into consideration the accuracy needed and the complexity of the studied system is required to perform real-time simulation. Computational capacity is increasing continuously and at a fast pace, and more complex simulation methods can be used for real-time simulation due to the continuous development of simulation algorithms and methodologies. Lately, faster-than-real-time simulation has become available. This new capability offers an interesting opportunity to improve machine behavior predictability in the near future via simulation, *e.g.*, by using a simulator to teach operators how to run the machinery so that mechanical stresses are minimized, which will result in longer machine life and possibly increased performance.

According to Shenghui *et al*. (2011) virtual sensors can be defined as software algorithms that utilize available measurements from the machinery to compute an estimate for the physical quantity of interest. Virtual sensors are also called soft sensors, because they are based on software. Virtual sensors do not directly sense the hardware as do traditional sensors (Fortuna *et al*., 2007). With respect to the information provided, virtual sensors can function the same way as any traditional hardware-based sensor. To add a virtual sensor, however, it is not necessary to purchase and install more instrumentation or add weight to the machine. To realize these cost and weight benefits, a validated simulation model is required that can estimate the measured quantity with an accuracy sufficient for decision making purposes. The virtual sensor can also be used to provide additional machine data. For example, insights could be made available into the dynamic behavior of the machine as introduced in by Inamdar *et al*. (2016).

In addition to the monitoring of machine functions, the virtual sensor concept can also be expanded to include the observation of human behaviors in the virtual models. This makes it possible to study the human movements needed to carry out assembly tasks, for example. This capability could be used to assess, *e.g.*, the ergonomics or timing of tasks in the manufacturing process (Gaisbauer *et al*., 2020).

8.3 Virtual sensors as a part of the product offering

The traditional approach to monitoring the condition of machinery has been to attach physical sensors to the locations that are most fragile or provide the most valuable information about machine performance or condition. These measurements are obtained using physical hardware sensors. Hardware sensor development continues at a rapid pace, and sensor pricing has decreased. Sensors with modest accuracy are cost-efficient. Even sensors with wireless capability are both economical and readily available.

However, hardware sensors are prone to failure, wireless sensors are usually battery operated with limited battery capacity, and wired sensors require direct connection to the data acquisition system. These deficiencies can be overcome by using virtual rather than hardware sensing, To exploit their full capability and to get accurate measurements, however, the implementation and continuous use of virtual sensors requires another type of engineering expertise above and beyond that needed to implement a hardware-based sensor solution. The following sections introduce the technical background basics needed to enable effective use of virtual sensors and some specific features that are associated with the used methods.

8.3.1 Technical methods enabling virtual sensing

To use any sort of virtual sensing, one must understand the available and applicable technical methods and tools. There are a handful of methods that have been developed over the years. Some of the simplest methods rely on linear analytic equations, which makes them attractive for analyzing simple cases where a linear relationship exists between the measurements and the observed parameter. On the other hand, advances in computational power and the development of more advanced numerical methods make it possible to conduct more detailed studies. The selection of methodology is always a trade-off between computational efficiency and accuracy.

Another significant feature that must be considered when planning to use the virtual sensing approach is if the virtual measurements can be done online or offline. Online calculation means the measurements must be performed in real time, whereas offline measurements means that the measurements are done independently of machine operation, which introduces an opportunity to use more accurate simulation methods since computation time is not a limiting factor. Typically, the most accurate model comprises a combination of different modeling techniques, *i.e.*, analytical equations, numerical solutions, and pre-calculated parameters. The model used as a virtual counterpart of the physical system can also be included in the PDM-system as a part of the product data.

Analytical methods

Usually, the analytical methods rely on equations that were developed decades or even centuries ago. Analytical equations are appropriate for simple cases where the interaction between different parts of the system are simple and where only a few parts are included. The relationships between these bodies can be simply described, *e.g.*, using linear relationships. Analytical methods are very efficient from a computational perspective. However, for more complex systems or when the interaction between different bodies cannot be simply described, the accuracy of analytical methods is not sufficient.

Analytical equations could be used as virtual sensors, for example, to estimate the weight of different objects using the linear relations between force (weight), displacement, and spring stiffness. As a practical case example, the weight of cargo loaded into a truck could be estimated knowing the spring stiffness of the truck suspension and the measurable push of the truck body after loading. Body displacement can be measured accurately using a very simple and cost-efficient linear potentiometer – familiar from the elementary school physics – and the analytical equation would be used to define the weight of the cargo without introducing complex and expensive piezo-electronic force sensors that would enable direct weight measurement. The accuracy of the weight estimated would not be as high as that provided by force sensors for this specific purpose, but the accuracy would be sufficient for most daily operations.

Although this may be an oversimplified example of a virtual sensor, it introduces the basic principle that the physical relationship between different measurements can be used to convert easily available information into a more valuable format.

Numerical methods

Numerical methods are usually used for more complex systems due to the limited capabilities of analytical methodologies. The development of numerical methods has been significantly accelerated due to achievements in developing microchips and other electronics enabling very powerful numerical computation. One of the numerical methods used most in mechanical engineering that can be applied to execute virtual sensing is the Finite Element Method (FEM). FEM is typically used to analyze mechanical structures and their behaviors by determining loads that occur during operation. The objective is to ensure that the structure can withstand the forces, pressures, and other loads without damage.

Systems are modeled in FEM using a number of finite elements that represents the system as a whole so it can be analyzed via numerical computation. Typically, a significant number of elements are needed to accurately describe a complex system, and the square of the number of elements is proportional to the computational effort that is required to solve these numerical problems. In the scope of the book, there is no need to get into more details of the finite element method and all the features of it, but on a general level, it provides a good basis for performing virtual sensing of object behaviors that cannot be straightforwardly measured if at all. The method gives access to the interior of structural elements not reachable using any hardware sensor.

One might question if FEM can be considered a virtual sensor due to its solid footprint as a numerical tool in machine analysis, however, in the context of virtual sensing, FEM makes it possible to build a virtual replica of a physical system and provide a virtual environment completed by measured input data enabling the analysis of computationally inaccessible but interesting system performance parameters.

Another method that has undergone significant development recently is simulation using multibody system dynamics. In multibody systems simulation, a mechanical system can be described as multiple rigid non-deformable bodies connected to each other by joints and forces. From the computation perspective, the system analysis solution is iterative. The state of the system – its positions, velocities, and accelerations – is solved numerically using matrix operations, which makes the method computationally expensive. However, continual increases in computational power and advanced algorithm development have brought about significant improvements in computational capability and efficiency, which in turn have now made it possible to solve multibody systems in real time or even faster than real time.

Another advanced technique in multibody systems simulation enables the modeling of flexible bodies by including the description of body deformations. This technique makes simulation via multibody system dynamics more accurate and adds the ability to estimate mechanical component durability.

The opportunity to calculate multibody systems faster than real time makes it possible to predict the behaviors of upcoming machine movements based on history data and the control signal from the controller to perform maneuvers or operations related to the expected working cycles. With faster-than-real-time solutions, the virtual model can predict, in advance, the optimal path to move a container from one place to another. The optimal path can be determined in terms of duration, fuel efficiency, mechanical durability, or other factors. These factors can be defined by the operator, machine manufacturer, or another relevant stakeholder responsible for the performance of the machine, lifecycle costs, safety, or any other important feature of the machine operation.

8.3.2 Opportunities/Benefits and challenges of virtual measurements

Virtual measurements can also be categorized based on computational pace. The categorization can be as straightforward as dividing the measurement into offline and online measurements. The definite factor controlling into which category a method falls is whether or not the measurement can be made in real time. Online measurement is available if computation time for a one-second simulation is less than one second. If not, the virtual measurement falls into the offline category. The following subsections introduce the opportunities and challenges of both categories.

Offline virtual measurement – slower than real time

Offline measurements can be slower than real time. In other words, minutes or even hours of computational effort can be applied to solve a one-second virtual measurement. The system model can be accurate enough to include non-linearities for interactions between different parts of the system, or it can include different aspects of the system environment. On the one hand, more intensive computational methodology can result is greater virtual measurement accuracy. On the other hand, it results in lower computational efficiency.

Offline virtual measurement can be used to study a wide range of different features of the details of a single component or of a complete machine assembly. Virtually, any existing simulation method can be used to perform offline virtual measurements, even methods capable of faster-than-real-time solution, *i.e.*, online measurement. Offline simulation enables the construction, for example, of lookup tables, where the parameters in the simulation model are pre-calculated and their effect on virtual sensor values are known in advance. During actual machine operation, the lookup tables could be used to guide movements instead of having to perform full simulations in parallel to determine the needed information.

The main challenge of offline measurements is the reliability of the virtual model. Accuracy is good, and it reflects the design selection of the user instead of introducing limitations from the computational perspective. Because of its offline nature, specifically measured data is needed beforehand to validate the model and the virtual sensor measurements. This must be an intentional procedure, which makes it inflexible and not applicable for systems that experience heavily fluctuating states over their lifecycle. For systems with states that fluctuate over time, the validation of the virtual model becomes problematic. An account manager or another responsible person must make sure that the model is updated and follows the actual conditions of the machine.

Online virtual measurement – faster than real time

In contrast, online virtual measurement requires the application of faster-than-real-time simulation methods. Every simulation time step must be solved in less time than the time-step simulated, *i.e.*, a one-second time span must be solved in less than one second. Online measurements are enabled by real-time or faster-than-real-time simulation methods. Real-time simulation makes it possible to engage the operator directly as part of the simulation model. To better engage a human as a part of a simulation, the simulation environment can be equipped with a regular display, virtual 3D glasses (such as Oculus), or even a motion platform that not only captures the visual aspects of the simulation, but also provides haptic feedback.

Real-time simulation can be used to adjust the driving parameters or control algorithms simultaneously when the machinery is running. It enables simulating multiple future scenarios in parallel using, for example, server clusters or multiple CPU cores. Based on the simulation results, the best scenario can be applied to maximize performance, extend service life, or prevent failures. With real-time simulation, simulators can be developed that give the operator an experience that feels like operating real machinery in the field.

Making online measurements or simulating real-time operation require computationally efficient methods. Analytical methods are the most applicable, but advanced computational analysis routines can also be used to perform multibody simulation in real time. However, multibody simulation does not deal well with unexpected events where the numerical methods are unable to resolve fast enough to sustain real-time simulation or cannot solve the problem at all resulting in a software crash. Online measurements can also rely on lookup-table approaches where the tables have been prepared using offline simulation methods. For example, the nature of contact between two parts can be pre-calculated using offline methods, and the forces in the real-time simulation can be recorded based on the pre-calculated and tabulated data for different operational scenarios or conditions.

The main challenges presented by online measurements relate to measurement accuracy. Successfully making online measurements requires simplifications to be made to maintain the necessary computational pace. These simplifications affect the accuracy of the results. This shortcoming can be minimized if the virtual model is continuously updated by feedback from the machine in operation. Moreover, it is important to continuously estimate the estimated error of the virtual measurement. Often case-specific tailoring of model parameters is required.

8.3.3 Business opportunities introduced by virtual sensors

Virtual sensors can provide added value in the different phases of a product lifecycle for different stakeholders in the value chain. Their most obvious use is as alternatives to physical sensors. Virtual sensors are typically used to monitor the system conditions and performance, and the monitored readings are evaluated and following actions taken by qualified engineers. Even though modern hardware sensors are connected to cloud services and monitoring can be done remotely, a large percentage of existing sensors must be connected manually to a data acquisition system.

Furthermore, the bandwidth needed to collect all the data is often limited, so data is not collected continuously when the equipment is in operation. Instead, data is gathered according to a planned measurement schedule such as once per day for ten minutes, for example. Virtual sensors offer the opportunity to do the heavy numerical calculation and data streaming in an internet of things (IoT) environment with virtually no limit to computational power or bandwidth. That makes it possible to monitor the machine system continuously, observing the changes of measurements as operational parameters or conditions change and collecting the data from hard-to-access locations.

Having better predictability of system performance and durability makes it possible to schedule maintenance as needed, which extends service intervals and reduces maintenance costs. It also helps to avoid expensive unpredicted service breaks due to failing machinery. OEMs can guarantee better predictability as a selling argument to the customer. The predictability can serve as a competitive advantage, or OEMs can improve their service businesses with the advanced monitoring capabilities. Service businesses can provide an additional recurring revenue stream raising the monetary value of a single installed unit and forging another link in the value chain via the upgraded value proposition. Alternatively, virtual sensoring can be sold as an after-sales product like software updates. This is a value-add proposition for the customer, because maintenance costs associated with detecting physical sensor faults and replacing the faulty sensors can be significant over the life of a product.

Virtual sensors also offer other valuable features. There are many R&D activities that occur before the mature product stage of the product lifecycle. With virtual sensors, the R&D team can more comprehensively consider the operational features of the existing equipment fleet. Data made available by monitoring machine fleet operations reveals actual changing operational conditions and environmental aspects ranging from in what industry and geographical area the equipment is operating to what is the expertise and experience of the operators. The better understanding of the affecting parameters provided enables better product design that takes into consideration specific conditions that can be further accounted for in control algorithms, user manuals, or service instructions, for example. From the manufacturing perspective the virtual sensor concept has the potential to reduce the number of physical sensors in the end product, which decreases manufacturing cost and the number of parts in the product bill of materials.

8.4 Conclusions

The chapter discussed the virtual sensor concept in the context of physics-based digital twins. The virtual sensor can operate offline or online depending on case-specific needs. In certain dynamic systems such as mobile machinery, for example, online sensing is required to get valuable operational insight. In static systems with only a few affecting parameters, offline virtual sensors can be used. In a product cost structure, the virtual sensor requires a different kind of investment compared to current sensor approaches, and professional personnel are needed for implementation and to ensure that accuracy is and remains at the desired level. The operating costs of virtual sensors is minimal and implementing them does not require changes to actual system components. However, the virtual model must be periodically updated as machine wear affects operation over the product lifecycle.

Recent developments in the technology, simulation algorithms, and computational capacity has made it possible for simulation models to include sufficient detail to represent complex machine systems with a high degree of accuracy and computational efficiency. The fastest analysis methods are based on analytical equations that describe the system through linear relations. The more complex numerical analysis methods are more computationally heavy, but they allow model complexity to be significantly higher without sacrificing accuracy. The achievable level of accuracy and computational efficiency is usually a trade-off between these two.

Depending on computational capability and the required effort, virtual measurement can be either offline or online. Offline measurement is slower than real time, *i.e.*, the computational effort to simulate a certain time span takes more CPU time than the length of the time span itself. In contrast, online virtual measurement is faster than real time meaning that calculation is performed in a shorter time span than the overall length of the simulation.

The introduction of virtual sensors and their use in different applications promises to further develop and increase the customization level of different products for customer-specific needs. Virtual sensors also help machine manufacturers by providing additional insights into machine operations. Because the interactions between internal and external behaviors can be monitored, increases in efficiency can be achieved, for example, by better focusing machine design on specific requirements and system level performance.

From a broader perspective, the virtual product makes it possible to operate the machine simulated at or near its physical limits within its virtual environment. As a result, less actual machine testing is required, which reduces labor and cost and the test results documentation needed to further utilize test results. However, making use of virtual sensors requires a different engineering skill set. Company management must recognize and accommodate this need to take full advantage of the virtual sensing concept. Virtual sensors require qualified engineering work, and the models need to be maintained continually.

Because the concept of digital twins is evolving and digital-twin research is currently very active, the formulations are still being finalized, and standardization is ongoing. The current lack of standardization is slowing integration of the technology and consequently, general benefits are not well understood. Pioneering companies are now becoming actively involved in development of the standards. For example, the ongoing "Digital Twin manufacturing framework - ISO/CD 23247" is currently being established. For business owners and entrepreneurs being a part of standardization opens a novel opportunity to be in the front line of the future virtual sensor business.

Policy makers should also understand the present lack of standardization. The business potential of digital twinning is clear, but practical business implementation of virtual sensors remains case specific. Standardization should also consider virtual sensor quality issues in the same way as product quality issues. In addition, liabilities that could arise from the misuse or misinterpretation of virtual sensor data should be considered so that responsibilities become and stay clear, and so that liability issues do not prevent widespread implementation of virtual sensors. To some extent, academia shares some responsibility to develop methodologies that provide more valuable digital tools for technology businesses, but also demonstrate and define practical limitations of the technology that should be taken into consideration by all the stakeholders.

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