

# Offline and Online Energy Simulation using Virtual Commissioning Models with Extended Dynamical Behavior

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**Abstract**—Considering energy consumption and dynamical behavior within the simulation of manufacturing systems emerges as an important objective for their development, commissioning, and operation. Currently, these aspects are often neglected in many fields including virtual commissioning. This work presents an approach to extend highly detailed virtual commissioning models of components from industrial automation by dynamics models for the calculation of energy consumption in an offline simulation and for reuse in an online simulation. To validate the presented approach, an exemplary offline virtual commissioning simulation of a pick-and-place robot application is implemented and subsequently transferred to an online simulation. The validation shows a good accuracy of the simulated energy consumption, enabling virtual commissioning engineers to analyze and optimize energy consumption already in the design phase of manufacturing systems. Additionally, the dynamical behavior was well reflected in the online simulation, contributing to the capability of simulation in the operation phase.

## I. Introduction and State-of-the-Art

The consideration of energy consumption in manufacturing processes has gained importance in the recent years [1]. Manufacturers are facing costs regarding CO<sub>2</sub> emissions, rising energy prices, and demands from climate-conscious customers. Furthermore, legal frameworks like the proposal for an Ecodesign for Sustainable Products Regulation (ESPR) presented by the European Commission in 2022 (including the concept of a Digital Product Passport (DPP)) will raise attention on product-related energy policies [2]. In the future, energy consumption will need to be analyzed already during the planning and development phases necessitating the use of simulation technologies [3]. Currently, the energy consumption and the dynamical behavior of manufacturing systems are often not considered in many fields of simulation in industrial automation.

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## A. Virtual commissioning

The early development and validation of programmable logic controller (PLC) code using a simulation model is known as virtual commissioning (VC). It increases quality and efficiency in production engineering by overcoming the need of the real machine in the development and commissioning process [4], [5]. A real-time simulation model of the machine, which often is referred to as a digital twin [6], is connected either to an emulated control system in a Software-in-the-Loop Simulation (SiLS) or via fieldbus to the real control system in a Hardware-in-the-Loop Simulation (HiLS) [7]. Through virtual commissioning, the basic kinematics of the manufacturing system can be tested, and the automation solutions can be validated with respect to different functionalities, special scenarios, or performance. Virtual commissioning usually focuses on the validation and optimization of PLCs instead of dynamical process simulation including energy analysis [4]. However, the kinematical and logical simulation models can be extended to include the dynamics of a system [8], e.g., to tune control parameters.

## B. Online simulation

The simulation of a manufacturing system with the simulation system coupled to the mechatronic system is known as online simulation. Online simulation can reflect the manufacturing system's actual behavior, for example to monitor the production process or to serve as a virtual sensor, but can also predict a future scenario, for example for resource planning or robot trajectory planning [9].

Models from virtual commissioning can be reused for online simulation to save modeling costs and efforts. However, depending on the application purpose, the models have to be extended as virtual commissioning usually focuses on kinematical simulation only.

## C. Energy simulation

The electricity consumption of an automation system can be calculated on different levels, where in many cases low granularity is given and constant consumption is assumed for each process state [10], [11]. Schmidt et al. [12] differentiate between calculating energy or nominal power and using simulation or empirical methods.

Within virtual commissioning, there exist several approaches to calculate electricity consumption: Gadaleta et al. [13] export the kinematical path of an industrial robots from the VC tool and use an external software

to calculate energy-optimized parameters. Hauf et al. [14] introduce the concept of using dedicated energy models in VC based on physical parameters to determine energy consumption. Damrath et al. [1] propose the use of physics engines to calculate energy consumption. While [15] apply the approach of extending digital twins from VC with dynamical models, they use simplified mechanical models for each axis of the researched robot and only consider a fixed efficiency factor instead of dynamical energy loss.

#### D. Paper outline

While Hauf et al. [14] and Damrath et al. [1] propose conceptual solutions for a top-down approach to calculating energy consumption, this paper follows a bottom-up approach. In contrast to Hollas et al. [15], which restrict themselves to the engineering phase, this paper offers an approach where the digital twin can be reused during the operational phase. Additionally, an accurate multibody dynamics model of the robot and highly detailed drive model containing the manufacturer's original firmware, which incorporates a drive-specific energy consumption model, are used within this work.

In the following section, the approach of extending VC models with detailed drive models by dynamics models for offline and online simulation is explained. Based on this, section III describes an exemplary implementation and validation of extended virtual commissioning and an online simulation of a multi-axes industrial robot, which shows the applicability and potential of the proposed approaches. Finally, a conclusion and an outlook into possible applications and future work is given.

## II. Energy calculation using digital twins with extended dynamical behavior

Component manufacturers increasingly provide realistic digital twins of their components for machine manufacturers to reduce effort when building up simulation models and to increase functionality of the models. Reusing these models and extending them saves modeling efforts, improves existing simulation technologies, and enables diverse new applications. This section deals with the extension of virtual commissioning models for the calculation of energy consumption in offline simulation and for the improvement of online simulation.

### A. Extended Virtual Commissioning Models for Offline Simulation

This work focuses on industrial servo drives, which usually are controlled by a PLC or computerized numerical control (CNC) via an industrial fieldbus. A highly detailed VC drive model contains the drive's comprehensive logical behavior, including the communication state machine, the operation state machine, the operation modes, and the controllers, as well as a motor and mechanics model. Depending on the used mechanics,

it has to be decided, whether an integrated mechanics model of the drive, which depicts the rotor inertia and possible oscillations, is sufficient or a connection to an external mechanics model, which reflects the manufacturing process and the related effects, is more suitable for a particular application.

Instead of using traditional kinematical models for virtual commissioning, which feed through the desired state, like a position command value, as the actual state, a detailed drive model is able to control a simulated dynamical system using the real closed-loop control technologies. The output of the drive model's controllers is used by a motor model to determine the actual torque of the simulated motor. Based on this torque, the dynamics model calculates the effects in the mechanics and feeds back the actual position of the drive axis as kind of a simulated encoder, which is an input for the drive's controllers, see Fig. 1.

In this paper, the concept of digital twins with extended dynamical behavior is applied [8]. A dynamics model is modeled in a domain-specific tool and imported into the VC tool as a black-box model where only the relevant parameters can be parameterized. This approach reduces the know-how and effort required from VC engineers. For the purpose of this work, rigid multibody systems are considered which are well suited for calculating forces that influence the energy consumption. These equations can be written in the following form [16]:

$$\mathbf{M}(\mathbf{y}) \cdot \ddot{\mathbf{y}} + \mathbf{k}(\mathbf{y}, \dot{\mathbf{y}}) = \mathbf{q}(\mathbf{y}, \dot{\mathbf{y}}) + \boldsymbol{\tau}_M. \quad (1)$$

In these equations  $\mathbf{y}, \dot{\mathbf{y}}$  and  $\ddot{\mathbf{y}}$  represent the generalized coordinates, velocities, and accelerations respectively, which serve as feedback for the drive controllers and  $\boldsymbol{\tau}_M$  the motor torques that are set by the drives.  $\mathbf{M}$  is the mass matrix,  $\mathbf{k}$  is the vector of generalized gyroscopic forces, and  $\mathbf{q}$  includes external forces such as gravitational forces and friction.

For the consideration of a drive's energy consumption, especially the actual output currents and the corresponding actual torque have to be reflected realistically in the drive model. The actual torque  $\boldsymbol{\tau}_M$  is necessary to determine the mechanical power  $P_{mec}$ , which is given as:

$$P_{mec} = \boldsymbol{\omega} \cdot \boldsymbol{\tau}_M, \quad (2)$$

where  $\boldsymbol{\omega}$  is the rotational speed of the rotor. Furthermore, the power loss has to be determined. Ohmic loss  $P_{ohm}$  usually is the most significant part and is estimated based on the actual output current  $I$  and winding resistance  $R$ :

$$P_{ohm} = I^2 \cdot R. \quad (3)$$

Beside that, there are iron losses, mechanical losses due to friction in the motor, and losses in the inverter, which base on individual characteristics of the built-in power electronic components and the specific pulse width modulation. These losses comprise dissipation within the semiconductors, chokes, and capacitors. As the corresponding technical data often are not published by the

drive manufacturers, it is hard to model the power losses for external parties. However, drive manufacturers may provide corresponding models integrated into the drive simulation models or as black box models separately.

In summary, the use of a dynamics model and actual forces in the simulation leads to a realistic modeling of the drive's output current, allowing for the calculation of mechanical energy based on the torque and velocity, as well as electronic power loss based on the actual output current and drive-specific characteristics. Detailed modeling of the drives' logic behavior leads to a more realistic reflection of the real manufacturing process and therefore improves the accuracy of the simulation results.

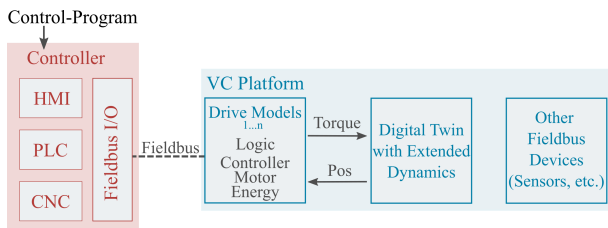


Fig. 1. Schematics of offline HiLS setup for energy simulation

By using real-time capable HiL virtual commissioning models and a suitable simulation platform, the simulation can be connected to an industrial control system via an industrial fieldbus (see Fig. 1). The control system runs common applications, like a PLC, CNC, HMI (Human-Machine-Interface), and a fieldbus driver, which interact with simulated automation components, like a virtual servo drive. By using extended virtual commissioning models as described in this section, the programmed manufacturing processes can be tested and analyzed not only based on kinematics, but also based on the dynamical behavior, such as the energy consumption of the considered processes. The prediction of a manufacturing process's energy consumption can be used to compare several options and to optimize the process.

### B. Extended Virtual Commissioning Models for Online Simulation

An online simulation at field level can reuse the simulation models and platforms from virtual commissioning to support the mechatronic system during its operation [17]. To reflect the actual behavior of a real mechatronic system within the online simulation, the simulation has to receive the same inputs as the real system. In the case of simulated field devices, these inputs are usually given by the control system via the fieldbus (see Fig. 2). Based on these inputs, the simulated components' behavior has to reflect the real system in a realistic manner. In the operation phase, not only the purely kinematical sequence but also the dynamical process behavior is relevant, as the simulation does not focus on testing the control system, like for virtual commissioning, but on gaining information on the mechatronic system and

the manufacturing process [18]. Hence, to also include the manufacturing processes' dynamical behavior and to improve the online simulation, the corresponding models have to be extended.

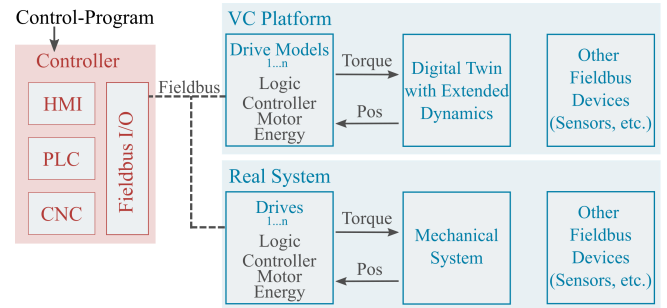


Fig. 2. Schematics of online HiLS setup for energy simulation parallel to the real system

In the case of industrial servo drives, the logic behavior is directly coupled to the dynamical behavior of the mechanics. Besides the drives' controllers, which effectively determine an output current – and therefore a resulting torque – based on the current motion, also the drives' state machines are influenced by the physical behavior. For example, error reactions resulting from overload, configured motion or power limits, or operation mode specific errors lead to reactions within the firmware's state machines. Hence, to accurately reflect the real drives' behavior in an online simulation, a sufficient modeling of the controlled mechanics' dynamical behavior is necessary. Considering this, an online simulation can be used for monitoring, anomaly detection, or virtual sensing within a manufacturing system.

## III. Implementation and Validation

The methods presented in section II are validated first in an offline VC simulation and then in an online simulation running in parallel to the physical process. As the focus of this paper lies on employing high-fidelity drive models in conjunction with multibody dynamics models, a pick and place robot application is chosen. For this purpose, a motion using two degrees of freedom measured on a real robot setup from [9] is replicated in the experimental setup. The modeled robot is a Kuka KR10 six-degree-of-freedom industrial robot.

### A. Offline Simulation

For the implementation of an offline HiL simulation, it is assumed that the robot uses two ctrlX DRIVES and MSK050B-600 servo motors by Bosch Rexroth, as a highly detailed simulation model is provided for these servo axes. The simulation runs in ISG-virtuos on an ISG real-time target, which enables deterministic real-time simulation with a step size of 1 ms and is connected to a ctrlX COREplus X3 control system via an EtherCAT fieldbus with a cycle time of 2 ms. The control system runs a PLC program controlling a positioning sequence.

The simulation receives the fieldbus telegrams and forwards the data to the corresponding simulation models. In this case, the master data is the input for two instances of ctrlX DRIVE simulation models, which represent the logic behavior of the two considered servo axes by incorporating large parts of the real drive firmware. The drive models also support the original parameter system to be communicated via acyclic communication, which enables to transfer configurations between real and simulated drives easily. To realize the positioning sequence, the simulated drives run in the drive-controlled positioning operation mode, where the drive interpolates the trajectory based on parameters given by the control system. When positioning is triggered through the positioning control word, the axis starts moving towards the target position. For this, the simulated drives' controllers determine an output, which results in an actual torque. Depending on this torque, the behavior of the robot is determined using a rigid multibody model. The rigid multibody system of the robot in the shape of equation (1) was modeled in the domain-specific multibody software Neweul-M<sup>2</sup> [19] and imported in the VC tool. The resulting angular positions are fed back to the drive models, where they serve as an input for the positioning controller.

Concerning the drives' energy consumption, the power supply and the loss at the DC bus are not considered in the following, as this requires additional assumptions on the technical configuration of the mechatronic system and considering the interaction of the power supply behavior with several inverters. Instead, only the energy consumption of the separate drive axes is simulated here. The used drive models contain an energy counter that estimates the energy consumption based on the mechanical power as well as ohmic losses of the motor and losses of the inverter's power electronics. Determining the power loss depending on the output current has the advantage, that the inconsistency of the efficiency is reflected and inefficient operating ranges could be identified already at the virtual commissioning stage.

The drives perform one up-and-down pick-and-place motion controlling the torque on the mechanical system, see Fig. 3. During the motion, the simulated drives measure the energy consumption, and the values are sent to the control via the same fieldbus interface as on the real drives. This allows VC engineers to analyze energy consumption during the commissioning phase while designing the control application. In this example, the consumed energy first rises due to the upward motion, until the robot stops and parts of the braking energy are recovered. After a short phase of acceleration, parts of the previously induced potential energy are recovered by the downward motion.

Using the presented method with existing component models from the manufacturers and importing dynamics models from domain specific tools as part of the digital twin, means that obtaining the consideration of energy

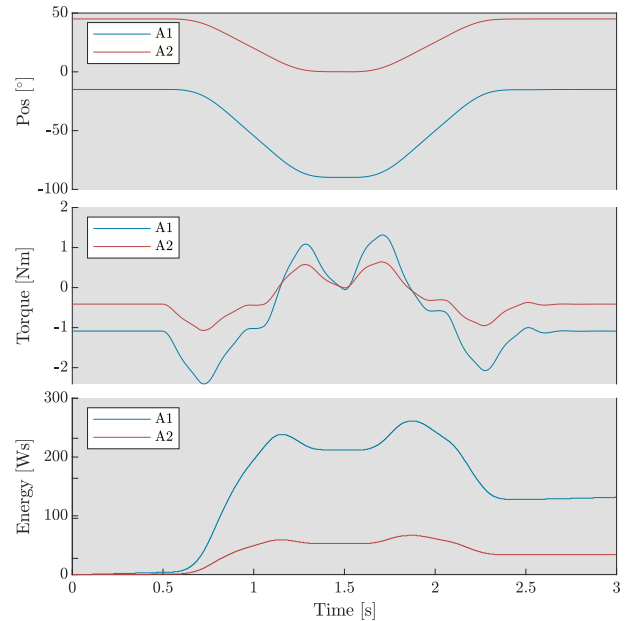


Fig. 3. Simulated signals for position, torque, and energy consumption in offline simulation (A1: Axis 1, A2: Axis 2)

consumption requires little additional know-how and time from the VC engineers. Consequently, it is possible to analyze and optimize the energy consumption of servo drives in the design phase of a manufacturing system.

## B. Online Simulation

To demonstrate the applicability of the extended virtual commissioning models for an online simulation and to validate the results of the offline simulation, a demonstrator is used, which uses an industrial control system (ctrlX COREplus X3 by Bosch Rexroth) with real servo drives as field devices. However, the demonstrator does not include real mechanics but bases on a servo motor coupled to a load motor, which applies a load torque corresponding to the behavior of the robot specified in section III-A by using the corresponding dynamics model together with a compensation of the real inertia and linear velocity dependent friction. By this, a realistic operation of an industrial servo drive is attained without the need of a real machine. The demonstrator bases on the implementation of Deubert et al. [17] and is schematically depicted in Fig. 4.

In addition to the real servo drive (ctrlX DRIVE XMD1-W1616 inverter with a MSK050B-600 synchronous servo motor by Bosch Rexroth), an ISG real-time target with ISG-virtuos as a simulation platform is integrated via the EtherCAT fieldbus. The simulation step size is 1 ms, while the fieldbus cycle time is 2 ms. In Fig. 5 a photo of the hardware demonstrator is depicted.

For comparison, the same motion as in the offline simulation is performed on the hardware demonstrator. The experiment only considers axis 2 of the previous setup. In Fig. 6, the position, torque, and energy consumption of

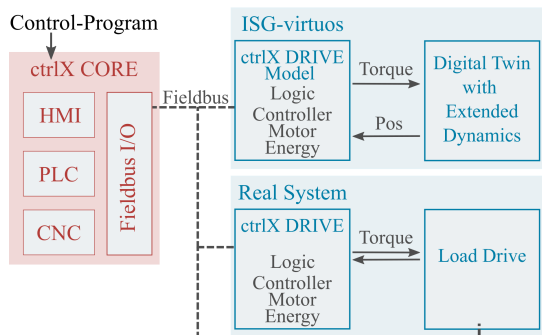


Fig. 4. Schematics of hardware demonstrator with online simulation

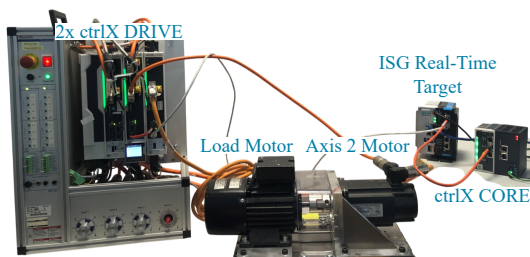


Fig. 5. Photo of the hardware demonstrator

axis 2 are displayed for the real drive, the simulated drive and the offline simulation from section III-A. Further, a generic user model for the motor was implemented based on information available in the published drive documentation. This allows for comparison of a generic motor model that a VC engineer can create if no digital twin is provided by the drive manufacturer. This estimation only considers the mechanical energy and ohmic losses (see equations (2) and (3)) and is depicted as "User Model".

On a kinematical level the measured positions match the simulated positions from the online as well as the offline simulation well, while there is only a small deviation, where the jerk is high. The good correlation of the offline simulation to the online behavior is due to the identical interpolation of position command values according to the identically configured positioning profile, which is followed by the closed-loop controllers of the offline simulation, online simulation, and real scenario.

The torque values show a generally good correlation but disturbances resulting from effects within the demonstrator, like friction or cogging torque, result in deviations between the simulated and real torque. Nevertheless, the remaining deviation is sufficiently small to consider the imitated dynamical behavior of the robot as realistically and consistent to the simulated dynamics, which is important for this validation.

Qualitatively, a good correlation between the actual and simulated energy consumption is achieved independently from whether the simulation was performed online

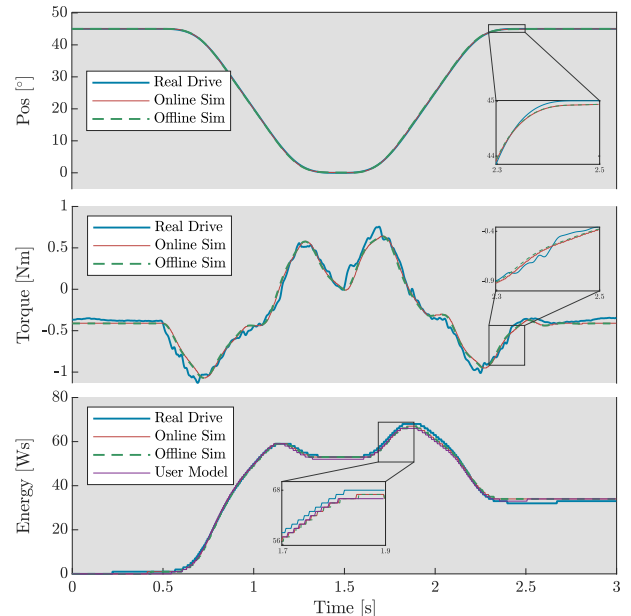


Fig. 6. Measured and simulated signals for position, torque, and energy consumption of axis 2 in online and offline simulation

or offline. As expected, the online simulation, which simultaneously reflects the behavior of the real drive, has the lowest mean relative error of 1.48 %, followed by the offline simulation, which only is slightly worse with 1.51 %. Moreover, the generic user model led to a good result with a mean relative error of 2.24 %. However, the comparison only considers the indirect measurement of the real servo drive and no direct measurement of the consumed electric power.

Modeling of the electrical power loss only has relatively low impact in this scenario, as the servo axis runs in an operation range, where it is highly efficient. At operation ranges with low efficiency, like at high torque and low speed, the modeling of power losses is more relevant.

Note that the resulting errors concerning the energy calculation relate to the drive model and effects within the used demonstrator, which result from the deviating torques. The dynamical process behavior has to be considered as perfectly modeled in this implementation, as the dynamics model used by the simulation is the same which the imitated real behavior bases on. In practice, the errors induced by the demonstrator are not present, but conversely, the imprecise modeling of the used robot's dynamical behavior could increase the error.

#### IV. Conclusion and outlook

This paper presents a novel approach to extending virtual commissioning models with rigid body dynamics models and highly detailed drive models for the calculation of energy consumption in both offline and online simulations. The method was validated through the implementation of an offline HiLS and an online simulation of a pick-and-place robot application on a

hardware demonstrator.

The results show good accuracy of the energy consumption simulation, meaning that the presented method enables VC engineers to analyze and optimize energy consumption with little additional know-how and time already during the design phase of a manufacturing system. This contributes to the design of more efficient production sequences and balancing of peak currents, which are costly for the machine operators. The proposed approach could also be used to coordinate production sequences to directly reuse the recuperation energy within DC networks.

In the context of online simulation at field level, the exemplary implementation showed that an accurate reflection of a dynamical manufacturing system is possible with the proposed approaches. Such an online simulation can be used to monitor a production process or to detect anomalies by comparing the simulated torque, showing an ideal behavior, to the actual torque. Furthermore, an online simulation can be used as a virtual sensor for quantities, which are costly, circumstantially, or not at all measurable by physical sensors.

The approaches of this work are not only applicable to the emphasized example of an industrial robot's servo axes but also to more complex manufacturing systems. For this, the simulation models have to be extended by a model of the DC bus and a power supply to also consider the power loss and interactions of multiple servo axes here. Additionally, there has to be a process model for the manufacturing process besides the handling by the industrial robot, if there is any. Concerning the computational load of the simulation, there are multiple approaches to achieve scalability for large simulation models. Besides the steadily increasing computational power of simulation devices, the simulation is run in a co-simulation, which means that there are multiple solvers which could be distributed to multiple CPU cores to speed up the simulation time.

Future work should focus on further validating the presented methods on different real-world applications of offline and online simulation and explore options to optimize energy consumption with regards to total energy consumption and reduction of peak currents.

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