Digital Twins for increased Sustainability in Manufacturing

AAS and FMI for Robotic Production Modules

#FMI #robot #analysis #optimization

To enhance the sustainability of robotic production modules, energy consumption and carbon emission should be considered during the design and the production planning phase. Virtual Commissioning (VC) of robotic production modules must therefore be equipped with sustainability parameters to allow the selection of the optimal robot and the mounted technology for a given production task during the early phases. The approach of integrating sustainability analytics and optimization based on standards during the design of production modules enables increased sustainability in robotic manufacturing.

Um die Nachhaltigkeit von Roboterproduktionsmodulen zu verbessern, sollen der Energieverbrauch und die CO_2-Emissionen während der Entwurfs- und Produktionsplanungsphase berücksichtigt werden. Die virtuelle Inbetriebnahme (VIBN) von Roboter-Produktionsmodulen muss daher mit Nachhaltigkeitsparametern ausgestattet werden, um die Auswahl des optimalen Roboters und der Montagetechnik für eine bestimmte Produktionsaufgabe in den frühen Phasen zu ermöglichen. Der Ansatz, Nachhaltigkeitsanalysen und -optimierungen auf der Basis von Standards in die Konstruktion von Produktionsmodulen zu integrieren, ermöglicht eine erhöhte Nachhaltigkeit in der Roboterfertigung.

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1. Introduction

In the MODAPTO project [1] the design, testing, and optimization of robotic production modules is targeted. An important aspect apart from efficiency and cost is sustainability. A robotic production module in the context of MODAPTO consists of an industrial robot and its mounted technology. The design of such modules shall be supported. The creation of standardized Digital Twins (DTs) is a central aspect to achieve standardized, reusable, flexible, and interoperable solutions. The project provides open-source software support based on the Asset Administration Shells (AAS) and Functional Mock Interface (FMI) standards. This helps e.g., to compare sustainability parameters of different robot sizes (e.g. bigger or smaller robot with mounted identical roller hemming heads) or different tools (e.g. electrical and pneumatical spot welding guns) during the planning and engineering of new production modules [2].

2. Preliminaries

To adhere with the goal of standardized solutions, the current state of the art must be taken into account.

2.1 Functional Mockup Interface

FMI [3] is a standardized way to exchange simulation models of dynamic systems. Such a model is called a Functional Mockup Unit (FMU). The FMI standard defines types of FMUs for different use cases. In practice, the most relevant use case is the co-simulation of time-continuous and -discrete simulation models. The standard defines an application program interface (API) to interact with the model in the FMU: the FMU is considered an entity with an internal state machine. The surrounding software, that executes the FMU to simulate the embedded model, has a set of methods to act on the model and the state machine. The well-suited calling of these API methods allows the simulation environment to remotely control these.

The FMU is a specially crafted zip file containing the actual implementation of the model in the form of executable code. The code can be either shipped pre-compiled or built on-the-fly if the sources are shipped. Both approaches have their individual benefits, but in most practical cases, the sources are pre-compiled and attached in binary form.

2.2 Asset Administration Shell

The AAS is a standardized way [4] to store and access information about an asset based on a DT including a digital model accessible via an API. The meta model defines a structural and standardized way to store the data and defines different file formats for exchanging the data.

To make use of the meta model and make it interoperable, the AAS uses so-called submodels. Such a submodel is a description of data attached with an AAS for one specific aspect or domain. For example, the submodel described in [5] defines a way to attach simulation models like FMUs to an AAS. The submodel specification defines which information is required or optionally available in the context of exchanging simulation models. Various submodels in different states and versions are available at [6]. These can be combined as needed. This plug-and-play approach allows for flexible usage of the AAS.

2.3 From Kinematics to Kinetics and Energy Models

VC is the process of creating and analyzing a digital prototype of a physical model to predict its performance in the real world and reduce time and effort for physical commissioning. The focus is on the control logic of robots and PLCs. This means that the behavior is tested before physical commissioning. In VC of highly automated production systems, typically, it is sufficient to describe the positioning of the movable parts of a production plant. Such movable parts are robot bodies but also miscellaneous parts like turntables, grippers, or conveyors.

To improve sustainability energy consumption should be considered as part of the overall performance of a production module or plant. Thus, models to simulate energy consumption and carbon emission of the production modules are needed. It would be possible to evaluate energy consumption using additional physical sensors, but this is often too expensive. The approximation of the energy of such a plant (already during design phase) must be done based on the movements of the parts and the corresponding motors. Depending on the trajectories of the positions, the momentary power needed in the motors can be calculated. Monitoring of the total energy consumed by the production module is possible by numeric integration.

The power at a given time instance depends not only on the position and speed of the moving parts. Instead, it depends on the acceleration of these parts. Thus, pure kinematic models that are normally used in VC are not sufficient to describe power consumption. Instead, kinetic models, that take acceleration and forces into account, are needed.

3. Physical Model Description

A robotic production module to be modeled can be seen as a set of rigid bodies that are interconnected by joints. This is called a multi body system. The motors attached introduce external forces between the bodies. This is well known and basic part of technical mechanics [7]. A concrete example of such a model is present in [8] which is more detailed than the model presented here. The simpler model probably allows for better application in trajectory optimization later.

3.1 Robot description

A model should be generated that calculates the carbon emission of a robotic production module based on the trajectories of the actuators and the external forces. To cover this problem, it is separated into different aspects. First, a mechanical model of the robot is generated. Next, the motors are to be modeled as well as the power electronics and control devices. Then, the energy consumed during a time span can be calculated. Additionally, the carbon emission can be derived based on the consumed power.

Robots and automation systems are not arbitrary multi body systems. These systems are crafted and designed for maximum flexibility while retaining easy control of all movements. There

Figure 1: A fictional 6DOF roboter (AI generated image by ChatGPT/Dall-E, 2025-09-26).

are a few best practices that have been established in robotics which allow to efficiently formulate the kinematic and kinetic models [9].

As a use-case, a 6 degree-of-freedom (6DOF) robot is considered. These are standard types in industry available in different sizes depending on the need. These robots all have a similar structure: there are 6 rotary joints in a serial kinematic, where two joints allow for axial rotation (see Fig. 1). The example robot for this contribution has a hem roller attached to fold thin sheets of steel.

3.2 Simplifications and Assumptions

Some assumptions were made to create a simulation model as accurate as necessary keeping it as efficient as possible:

- The robot bodies are stiff and rigid. There is no deformation or vibration in them.
- The robot controller works perfectly. There is no tracking error and no delay.
- The motors and power electronics have constant efficiency for all speeds.
- The breaks of the robot do not consume energy.
- The external forces of the hem roller are small in comparison to the gravitational force of the masses of the arm. Thus, the external force by the hem roller is currently neglected.
- The robot is assumed to have pure serial kinematics.
- The electrical part is significantly faster than the mechanical system. No electrical dynamic is modeled.

3.3 Mechanical system

In general, the positions of the actors (motors) of the robots are known. Using the forward kinematics [9], the absolute positions of all arm bodies can be obtained. Starting at the base of the robot, this problem can be solved iteratively by simple matrix operations. The corresponding derivatives lead to velocities and accelerations.

To calculate the power consumption of the robot, the moments in the actuators are needed. A kinetic model is required. State-of-the-art methods exist to calculate kinetic models, e.g. [9]. For pure serial kinematics such as 6DOF robots, a simplified approach can be obtained.

The calculation starts at the end effector and iteratively adds one body at a time until the robot base is reached. For the newly added body, all forces/moments are given except for the force/moment pair applied by the joint towards the base. By applying the principle of d'Alembert or similar [7] these can be expressed based on the position trajectories. Projecting the moment on the joint's orientation, the required motor moment is evaluated.

In summary, the iterative approach presented here allows to explicitly calculate the kinetic variables without solving non-linear systems of equations using e.g. Newton's method.

3.4 Electrical system

By the assumptions, the motor and gear box do not provide any dynamic behavior. The simplest model to consider is that these parts only represent constant efficiency factors. As a result, the electrical power of each motor can be directly calculated from the moments and speeds.

The electronics are assumed to not have a way to recuperate the energy from the robot (e.g. during deceleration). The power will be fed into a heater attached to the power electronics on a per-motor basis. So, the power electronics will draw either the required power of the motor from the grid, or no power is drawn (breaking energy is lost in the heater). By adding the per-motor power, the total grid power can be calculated.

3.5 Energy consumption and Carbon Emission

By integrating the electrical grid power, the electrical energy consumption can be obtained. The carbon emissions can be evaluated similarly by scaling the power with an energy mix factor that defines the carbon emission per energy unit used. This mix factor can be time-dependent, in which case the total carbon emission is numerically integrated separately.

4. Practical considerations

Apart from the actual model description some practical considerations are necessary.

4.1 Environment

The application in industry requires that the simulation model can be exchanged as part of a DT. This is achieved by incorporating it into an AAS-based DT using the submodel "Provision of Simulation Models" [5]. For the simulation model, the standard FMI is chosen among all possible models within the submodel.

To support FMI, the algorithm provided in section 3 was implemented and embedded in a shared library as requested by the FMI standard. This makes the approach generally reusable in all FMI-supporting kinds of simulation and VC software.

The FMU implementation aims for a minimal footprint and minimal (software) dependencies (e.g. Python interpreter or .NET framework) imposed on the execution environment. For the actual behavior implementation an object-oriented approach using C++ classes is used. To comply with the API defined by the FMI standard, a generic C Wrapper was developed. It hides the C++ dependencies (compiler version, STL, etc.) and exposes only the necessary API. This reduces complexity, simplifies FMU deployment, and ensures interoperability with the established C-based FMI infrastructure.

For simplicity, the FMU is split into two model kinds (c.f. section 3.5): One kind (energy consumption model, ECM) estimates the power consumption of a robot. The other (carbon emission footprint, CFP) covers only the model partition dealing with carbon emission. The latter is completely independent of the robot and can thus be reused in other contexts. The ECM FMUs come in different flavors addressing slightly different use-cases. All FMUs are provided as open-source models [10]. The interconnection between these ECM and CFP is depicted in Figure 2.

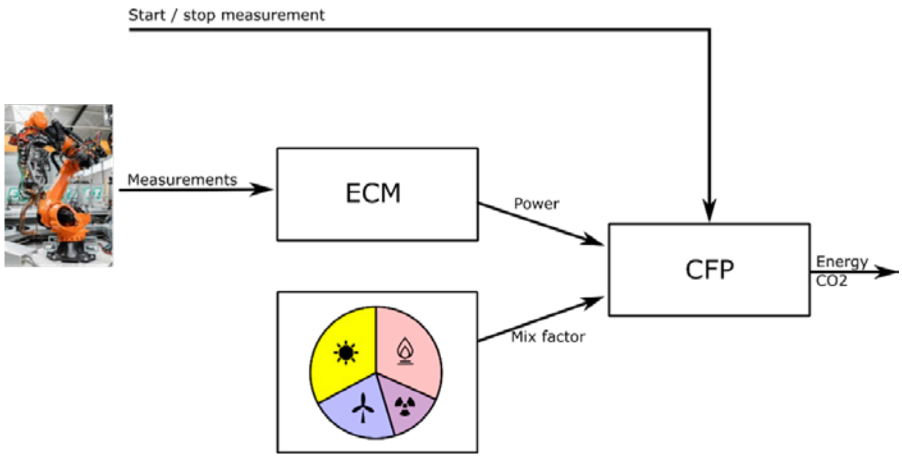

Figure 2: Interconnection of models and calculation of carbon footprint.

4.2 Interface of the FMU

The created FMUs have clear interfaces which may be found in [10]. The corresponding README file gives a quick overview of the available models. Depending on the used robot type and controller, electrical information is available and can be used or an electro-mechanical base model must be applied (ECM FMUs). The CFP FMU can use the momentary power to estimate the emitted carbon dioxide (CO_2) depending on the (time-variant) ratio of primary energy sources in the power grid called mix factor.

5. Utilizing FMU for Energy Optimization

The developed FMUs are not only designed for simulation purposes but are also intended to support optimization workflows aimed at improving the energy efficiency and support carbon emissions reduction of robotic systems. In the past, similar approaches have been applied focusing on single robot vendors and their proprietary solutions[11]. In this context, the FMUs acts as evaluators, providing estimates of both energy consumption and associated carbon emissions for given actuator trajectories independent of the robot vendor or version used. These trajectories, defined by joint position, velocity, and acceleration of each axis over time, are utilized to obtain motion profiles that give rise to corresponding variables for a properly defined optimization model [12].

To perform optimization, several candidate motion profiles are generated. These profiles serve as input to the ECM FMU, which evaluates the momentary power at each time step. By integrating the output power signal over the duration of the trajectory, the total electrical energy consumption is computed.

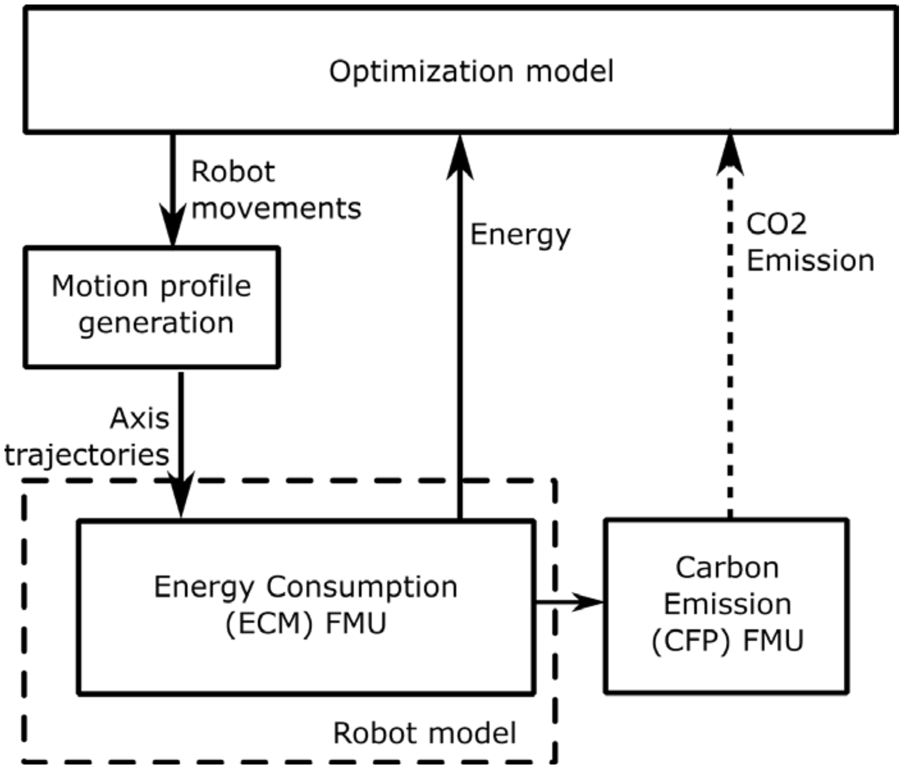

Figure 3: Optimization of the trajectories using FMUs.

Additionally, carbon emissions are calculated based on the evaluated power consumption and relevant emission factors. Each iteration queries the FMUs with a new candidate motion profile and receives estimates for both energy usage and estimated emissions. The evaluations for all provided motion profiles are then used to form the objective function and corresponding constraints of the optimization model, depending on the requirements of the underlying industrial setting. For example, a model may be built that enables energy minimization, with the emitted carbon emissions estimated as a by-product or utilized to impose constraints on the total carbon emissions for the work performed. The relevant mix factor cannot be predicted in the long-term, thus the optimal value might vary. As the mix factor in a practical setup only changes on a daily schedule, the optimized robot movements will not be affected as long as the optimization time horizon is lower than a day. The overall process is sketched in Figure 3.

This approach allows for the exploration of different motion profiles. For instance, optimization can be constrained to respect joint limits, velocity and acceleration bounds, and cycle time requirements. In addition to the primary kinematic inputs, it provides parameters for defining the robot's mechanical and electrical characteristics. Through this methodology, the FMUs become a flexible tool not only for simulation but also for optimization, supporting the development of motion strategies that align with the preferred sustainability objectives.

6. Summary and Outlook

With the models derived in section 3 it is possible to compare the estimated power consumption with the consumption of a real robot. This allows to verify the assumptions in section 3.2 are valid and create a simulation environment to be used in the robot program simulation as described in section 5. A practical set-up to validate the models is currently under construction. This will finally allow to evaluate the accuracy of the models generated.

The model can even be made more accurate by introducing models for a gear- box, refine the motor model (especially to take stalling current into consideration), add a model for the power consumption of the power electronics and controller, and also add models for the process (e.g. roller hemming). All these models must be such that they can be combined as the need arises in a plug-and-play fashion.

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