

# Methodology for Reusing Real-time HiL Simulation Models in the Commissioning and Operation Phase of Industrial Production Plants

Sebastian Kain<sup>1</sup>, Frank Schiller<sup>1</sup>, and Sven Dominka<sup>2</sup>

<sup>1</sup>*Institute of Information Technology in Mechanical Engineering, Automation Group,  
Technische Universität München,*

<sup>2</sup>*School of Electrical and Computer Engineering,  
Royal Melbourne Institute of Technology,*

<sup>1</sup>*Germany*

<sup>2</sup>*Australia*

## 1. Introduction

Automation Industry is dealing with productivity, costs, quality and flexibility in the manufacturing process. In addition to the classic requirements of increasing productivity, reduction of costs and increasing quality, flexibility plays a significant role in the modern manufacturing process. These requirements are fulfilled by development, adaptation, and application of advanced engineering processes and methodologies improving mechanics, electronics and software development. One methodology that is widely applied in the development of complex mechatronic systems is HiL Simulation. By definition, a HiL (HiL) Simulation is a system that combines parts of a real system with parts of its simulated counterpart (Stoeppler et al., 2005; Grega, 1999). It is one of the best-known methods for testing embedded systems (Yan et al., 2005; Boot et. al., 1999) by providing the possibility of validating software execution on the original hardware without the dangers that are evoked by a malfunction of the controller in combination with the real mechanic system (Pfister et al., 1999).

In the early stages of the production plant lifecycle, ranging from Basic Design to Plant Engineering, discrete event simulation models are created reproducing the behavior of the mechanic system. Supporting the engineering of the control system, these models are executed in a real-time environment and connected to the control logic for desk checks. At the end of the Engineering Phase, the application of HiL Simulation shifts to the virtual commissioning of the overall process control system (Deutel & Suhm, 2002; Rohrlack, 2008). The commissioning of modern mechatronic production plants is a critical cost intensive phase. At the beginning of the commissioning phase, the controller and its embedded control software and its correct interaction with the production plant are validated by HiL Simulation. These techniques strongly base on accurate simulation models.

Because of model inaccuracies between model and specification as well as between model and real plant, it is unlikely to find all errors in the controller software solely by controller testing with HiL Simulation. But even one failure in the controller may cause critical

machine states and damaging parts of the production plant. Thus the authors present a new approach for improving the commissioning of production plants. This approach, called Hybrid Commissioning, is an incremental procedure for commissioning that begins with a HiL Simulation, goes on with a mixture between reality and simulation, and ends up with the commissioning of the real production plant.

For achieving an optimal operation of the production plant, it is unavoidable to consider varying production conditions, e.g. in the flow of material or required retooling of components in the plant. Monitoring and diagnostics can support the operation of complex mechatronic systems and have to be provided efficiently. The authors present a methodology for reusing HiL Simulation models during the operation phase of industrial production plants. HiL Simulation models are used for determining the nominal state of the plant. Therefore, the HiL Simulation has to run in parallel to the real plant and has to be stimulated simultaneously by the control system. Initialized with the current state of the plant and the control system, a HiL Simulation can be applied predicting the behavior of the controlled plant. Therefore, the discussed application scenarios comprise the reuse of HiL simulation models for the purpose of monitoring and diagnostics as well as prognostics and optimization.

This chapter is structured as follows: In Section 2, fundamentals of industrial production plants are presented: production plants are structured according to their functionality and a summary over the lifecycle of production plants is given. The methodology of HiL is presented in the Engineering Phase of production plants and applications to mechatronic systems are discussed in general. In Section 3, the application of HiL Simulation methods in the commissioning phase by Hybrid Commissioning is introduced. In Section 4, two approaches for supporting the operation of manufacturing systems are presented: running a simulation model in parallel to the manufacturing system in Synchronous Simulation for purposes of diagnostics and using a simulation model in Forward Simulation for prognosis. Afterwards, application scenarios are discussed in Section 5. In Section 6, conclusions of the reuse of HiL Simulation in the Commissioning and Operation Phase of industrial production plants are given.

## 2. Fundamentals

This chapter deals with some methods and techniques that are recommended to apply during different stages of the lifecycle of production plants or production machines. These methods and techniques are based on HiL Simulation or rather HiL Simulation models. To gain a common understanding of these innovative approaches under the readership, this chapter is dedicated to general description of 'production plants', a generalized 'lifecycle of production plants' and the well known method called 'HiL' Simulation or 'HiL' Testing.

### 2.1 Industrial production plants

Industrial production plants represent complex mechatronic systems in factory automation machinery. There is a wide range of applications where production plants are used. Examples are wood-processing, packaging and various kinds of manufacturing of all sorts of products. Although automation industry is dominated by a few suppliers, industrial production plants are mainly built by small and medium-sized enterprises. Considering unique specifications, they are mainly built in individual production. Regarding this

constraint, the costs for development and commissioning are much more considerable than in markets with mass production and, hence, a cost efficient usage of engineering methods and techniques is essential.

Production plants are typically composed of modular sub-systems, so called production machines. In these machines, goods are processed in various ways. The machines are connected via feed systems, which move the products or goods from one unit to the next, c.f. Fig. 1.

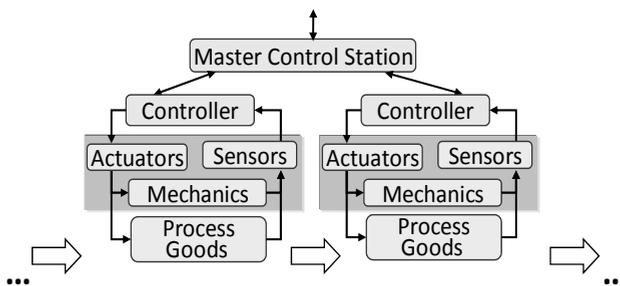


Fig. 1. Structure of a production plant

Production plants, comprising machines and feed systems, are built up of sensors and actuators, which typically represent mechatronic systems themselves, mechanical parts and different types of controllers. The type of controller depends on the functionality to be achieved. The functionality ranges from planning purposes at the top, e.g. realized in an operations control computer on process control level, to operational purposes at the bottom, e.g. a programmable logic controller on plant-floor level.

For structuring the functionality and the tasks of components in manufacturing systems, the Automation Pyramid is often applied (e.g. (Brown & Lean, 1987; IEC 2008), c.f. Fig. 2. In higher levels, real-time requirements are less important, whereas planning aspects gain in importance at the same time. In the Process Control Level, the process realized in the manufacturing system is planned in an optimal way regarding production constraints like availability of resources or priority of orders. In the Cell Level, the main task consists in evaluating and controlling the signals in the subordinated levels, e.g. several logic controllers or intelligent field devices. In the Actuator/Sensor Level, information about the process is gained via sensors and transmitted to the control system in the Plant-floor Level. There the information is processed according to the specified behavior and actuators are activated, while the data processing has to fulfill real-time requirements. In the Actuator/Sensor Level and Plant-floor level, real-time requirements play an important role. In regard of the designated process, dynamic or discrete properties dominate. Consequently, the task of the control system on plant-floor level range from executing step sequences up to advanced closed-loop control algorithms.

Depending on these different main tasks, different types of controllers are used. The programmable logic controller (PLC) is typically used event-driven or rather logic-driven step sequences. Numerical controllers (NC) are used for processes with very dynamical and highly precise motions, typically in machine tools (CNC machines). A controller type that combines the qualities of a PLC and a NC is a motion controller (MC). Such controllers are used for processes with fast and precise motions and logic-driven step sequences. A very

flexible controller that has the potential to substitute the PLC, the NC as well as the MC is the industrial PC (IPC): a PC system that is tailored to industrial needs and is based on a real-time operation system for that reason.

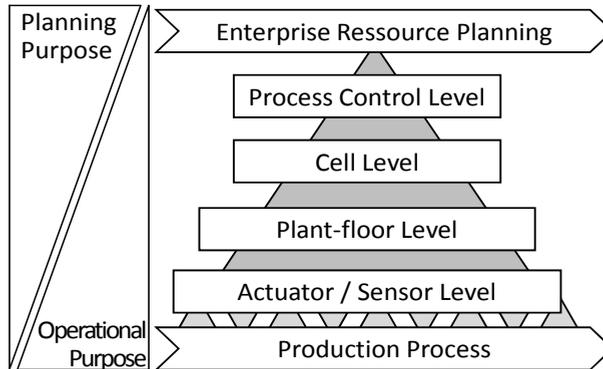


Fig. 2. Functional range of production plants in the Automation Pyramid according to (Brown & Lean, 1987)

Nowadays, industrial production plants have to feature high availability. Simultaneously, they have to produce as many goods as possible with the required quality. For cost-efficient production, the plant needs to be capable to manufacture different goods without any huge efforts in refitting (Wiendahl et al., 2007). Regarding optimal operation, it is necessary to consider changing conditions. To fulfill such requirements, production plants become more and more complex. The installed sensors and actuators are mechatronic systems themselves that embed controller with significant processing power. Examples are modern electric drives. Drives must fulfill requirements that lead to the above mentioned highly precised and speedy motions. Here, speeds of 10.000 rpm (rounds per minute) and accelerations of 12.000 rpm/s are common. To fulfill such requirements, drives are equipped with modern CPUs that are capable to run advanced control strategies.

One main enabler for the above mentioned functionality of production plants (and its varies sub-components) is software. The amount of software in a production plant is enormous and still increasing. And with the increasing amount of software, the effort for software development increases as well.

Production plants are of different qualities, each machine has its own efficiency. For evaluating the production plants, the Overall Equipment Effectiveness (OEE) was introduced merging capacity, availability, and product quality (Hansen, 2005; Nakajima, 1988). Parts of the OEE can be determined and fulfilled by the assembly during the development process, others, like availability are determined in the operation phase by several effects, e.g. improper handling, delays in the flow of material, abrasion or even the breakdown of components in the plant.

## 2.2 Life cycle of industrial production plants

Goal of this chapter is to introduce advanced methods for reusing Hil Simulation models to a broad audience. The introduced methods are applied in different phases of production

plant life cycle. Hence, a brief summary over the (earlier) stages of the production plant lifecycle is given, c.f. Fig. 3:

- In basic design, the essential functionality of the plant is defined. An optimal design of the plant requires the analysis of the production process as well as the required capability of the plant. Attributes like capacity, reliability, maintainability, and follow-up costs as well as the resulting quality of the produced goods have to be defined (Lenord & Brohm, 2007). By using rough geometric and approximated functional models, proofs of concepts are realized.
- During the phase of plant engineering, the basic design is extended and detailed. The plant engineering starts typically with the specification of the mechanics, is continued with the application of sensors and actuators, and leads to the development of logic controllers and control systems. The controller design can be highly supported by use of application-specific functional models (Dominka & Kausler, 2006; Deutel & Suhm, 2002; Haufe, 2006).
- During the procurement and manufacturing phase, the designed assembly of the plant is finalized.
- The commissioning phase comprises the start-up of the machine and the validation of its full functionality.
- During the operation phase, the plant produces the goods it was designed for.



Fig. 3. Lifecycle of production plants ranging from Basic Design to Operation Phase (Dominka & Kausler, 2006).

### 2.3 Methodology of HiL testing in the engineering phase of industrial production plants

HiL Simulation is a well known method that is applied during the engineering phase of mechatronic systems. It is generally used as a test method. By definition, a HiL Simulation is a system that consists of real hardware components and simulated components that are connected to each other and show a (closed-) loop character (Grega, 1999; Stoepler et al., 2005).

In industrial automation, there are different use cases for HiL Simulations. One use case is the testing of industrial components (system under test), like motors and drives. Here the real component is integrated in a simulation test-bed (test-rig), which integrates HiL Simulation models and additional real parts like counter-motors, emulating the torque load and the load against a real motor (Bouscayrol, 2008; Maclay, 1997; Oh, 2005; Lin & Zhang, 2008; Murakami, 2005), c.f. Fig. 4.

Another application of HiL Simulation is testing of the control software for modern industrial production plants. In this case, the system under test, typically a programmable logic controller or a motion controller, is connected to a simulation model of the technical process, consisting of the mechanical and electrical parts (sensors and actuators) of a production plant and the process good, which is also an essential part of the technical process. In other words, the physical parts like the mechanical components, the actuators,

the sensors, and the process goods are modeled in a real-time simulation system that is connected to the controller (Haufe, 2006), c.f. Fig. 5.

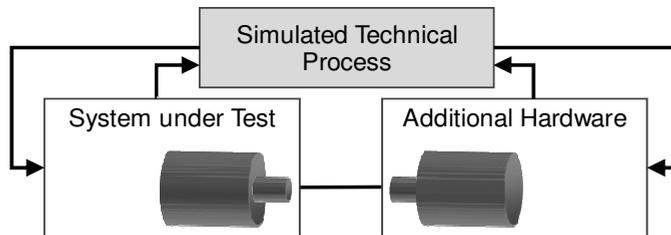


Fig. 4. HiL setup.

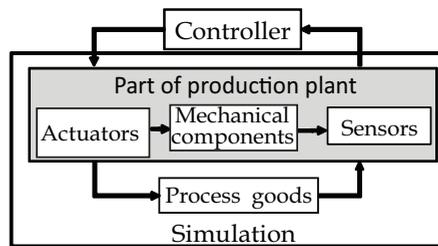


Fig. 5. HiL Setup in the realm of industrial production plants for controller testing

To be able to use HiL Simulation for controller and software testing, some very important requirements need to be fulfilled by the HiL Simulation models:

- **Realistic functional behavior:** The idea behind HiL Testing is that the simulation behaves in such a realistic way so that the controller does recognize the simulation as real machine. This means that the functional behavior of the simulation needs to be accurate enough, so that the controller works in its regular way.
- **Realistic timing behavior:** Technical processes, run by production plants or machines, are high dynamical, and so the controllers need to fulfill hard real-time requirements. To be able to test these controller characteristic properly, the HiL Simulation needs to run in real-time as well.
- **Communication interface:** The controller communicates with the machine via various communication interfaces (e.g. field busses). For testing, the controller must not be manipulated, i.e. the controller with its original hardware and software needs to be used. Hence, the HiL Simulation must provide the identical communication interface as its real counterpart.

HiL Simulation is one of the best-known methods for testing PLCs and motion controllers. It can emulate the plant behavior before the real plant is available. It provides the possibility of validating software without the dangers that are evoked by a malfunction of the controller in combination with the real mechanic system. Because this procedure can be considered as a commissioning of the controller by means of a simulated plant, it is known under the expression 'virtual commissioning' or 'soft commissioning' (Auinger et al., 1999; Wischnewski & Freund, 2004).

## 2.4 Application of HiL models in mechatronic systems

HiL Simulation is applied in various industries, like in the automotive and aerospace sector and in industrial automation. Especially for the development or rather testing of electronic control units (ECU), HiL Simulation is a very powerful and important technique that is widely used by automotive manufacturers and automotive component suppliers. Because of the high number of manufactured pieces in this industry, higher engineering costs can be better apportioned. This is also true for the modeling efforts, which consist in time and costs for building up the models that are necessary to prepare and run a HiL Simulation.

Unfortunately, this is not true for the realm of industrial automation. As mentioned earlier, production plants are themselves built in job production, which leads to the fact that engineering budgets are much more limited than e.g. in the automotive industry. The development of HiL Simulation models is therefore too costly for many companies in the industrial automation, and although its benefits are proven, HiL Simulation is often not applied.

Fortunately, the use of HiL Simulation models is not only restricted to software testing. By (re-)using such models, benefits can be achieved in the commissioning and in the operation phase of industrial production plants, and, furthermore, a justification for the modeling efforts can be achieved. In the following sections, some of such methods are presented

## 3. Application of HiL simulation methods in the commissioning phase

The commissioning of production plants is a very complex as well as a critical process in the lifecycle of production plants. Commissioning is defined as the transfer from the non-operating state of the production plant after assembling into the operating state of production. "The goal of any commissioning effort is to energize the equipment safely, in the time frame dictated by construction completion and process startup plans." (Bowen, 2000). Depending on the production plant and its dimension, assembling for the purpose of testing at the engineers place is not possible or very uneconomical. Thus the production plant is often assembled for the first time at the customers place.

Due to the increasing interdisciplinary between mechanical, electrical, and software components, it is hard to test one component without the availability of the remaining components. Consequentially during commissioning phase, the whole production plant is activated almost at once. Issues with parts of the plant or interfaces between components must be resolved one after the other. As a result the commissioning phase often takes an unjustified long time and costs a lot (McGregor, 2000).

Due to the increasing ratio of software in modern production plants, also the commissioning of these software components and the control unit/embedded system get more time-consuming. The costs for commissioning the controller and the embedded software exceed the costs for commissioning the mechanical components and are continuously increasing. The duration of the complete commissioning phase to the engineering phase takes about 15 to 25%. Thereof the commissioning of the electrical and software components takes about 90%. The reason for this high rate is in 70% due to software failures. The controller software therefore could take 60% of the commissioning time and 15% of the complete engineering time (VDW, 1997). Hence, there is a high industrial demand to increase the efficiency of commissioning the controller software.

### 3.1 Techniques for reducing the efforts of commissioning

There are several techniques how the efforts of commissioning could be reduced. These techniques can be classified as direct and indirect techniques and also constructive and analytical techniques. Direct techniques are used directly in the phase of commissioning contrary to indirect techniques, which are used in former phases and affect the commissioning indirectly by increasing the quality of the production plant or its components.

Analytic techniques are applied for the detection and localization of failures. All testing and checking methods are therefore analytical ones. Constructive techniques by contrast aim on high quality during the engineering. That means that constructive techniques avoid the appearance of failures.

In (Rieger, 1995) some of these techniques are described exemplary:

- A systematic requirements analysis for avoiding expensive aberrations (indirect, constructive)
- A systematic software-engineering with the phases 'concept', 'implementation' and 'test' should reduce errors during the development (indirect, constructive as well as analytic)
- Reuse of software-components for combining the advantages of high quality software and low development efforts (indirect, constructive)
- Pre-checking of machine and plant components before assembling the machine for recovering failures previously to the commissioning. (indirect, analytic)

Approaches during the commissioning phase comprise structured, checklist-based procedures and various tools, like monitoring, parameterization, and diagnostic tools.

### 3.2 Hybrid commissioning – incremental procedure from virtuality to reality

The main goal of HiL Simulation is to test the controller and its embedded software, and to find remaining software errors. In spite of the big advantages of HiL Simulation, it is not guaranteed that all software bugs can be detected. Because of discrepancies between the real and the simulated plant, it is unlikely to find all mistakes in the controller software with HiL Simulation. But even one failure in the controller may cause critical machine states and damage parts of the production plant. Because of this fact, the procedure of commissioning has to be executed very carefully. Nevertheless, it is possible that a failure in the controller occurs, so the machine could be damaged and the commissioning phase could be hold up further more. In addition, it might burry the risk to endanger human life (Schludermann et al., 2000).

This risk can be reduced by applying a technique called Hybrid Commissioning. Hybrid Commissioning is the stepwise transfer from the non-operating state of the production plant after assembling into the operating state of production by use of HiL Simulation (Dominka et al., 2007a; Dominka et al., 2007b; Dominka et al., 2007c). The rate of the real to the simulated components increases in the course of the commissioning procedure. In the beginning, a completely simulated plant is connected to the controller, whereas at the end the ratio of reality has been increased up to 100%. By applying this procedure, damages to the production plant and the process goods during commissioning can be avoided, and the commissioning can be performed less risky, more safely, and less time-consuming.

The procedure of Hybrid Commissioning is classified and presented in detail: 1) HiL Simulation, 2) partial commissioning of actuators and sensors, 3) Simulation-of-Goods, 4) commissioning of the real plant.

### Phase 1: HiL Simulation

Phase 1 of the Hybrid Commissioning is the complete HiL Simulation, c.f. Fig. 6. The purpose of this phase is to detect most software bugs in the control unit and mainly to check the controller for correctness. The big advantage of this phase is the avoidance of real danger to field service personal, machine or process good in the case of a wrongdoing of the controller. However, a disadvantage arises. It is only possible to check the behavior of the controller while communicating with the simulation. Due to discrepancies between reality and simulation, it is not possible to obtain exactly the same behavior while connected to the real plant. This phase is finished, when the controller connected to the simulated production plant works as demanded.

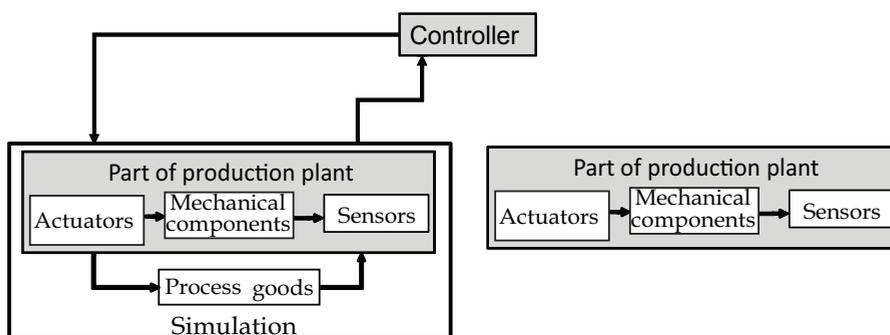


Fig. 6. Phase 1: HiL Simulation

### Phase 2: Partial commissioning of actuators and sensors

In phase 2 of the Hybrid Commissioning, the actuators and sensors of the production plant are started up stepwise. The goal of this phase is to check, whether the single components themselves work correctly. In the beginning, the HiL simulation is connected to the controller like in the 1st phase. After that, control commands are additionally sent to particular real actuators step by step. That means, that the control unit communicates with the HiL simulation, but the control commands are also sent to selected actuators. In this manner, it is possible to check the communication and operability between the control unit and real actuators. Malfunction could point to an error in the actuator, e.g. a wrong configuration or an error in the control software, c.f. Fig. 7.

Another goal of this phase is the check of sensors. Although the control unit still communicates with the HiL Simulation, it is possible to check the state of certain sensors and for example compare them with the simulated ones. As there is still no good to be processed in the real production plant only these sensors could be checked that are triggered mechanically by the production plant itself and not by the good. Light barriers are for example often used to be triggered by the good whereas encoders are triggered by a mechanical component. After verifying these sensors, it is possible to send the state of the real instead of the simulated sensors to the controller.

The advantage of this phase of Hybrid Commissioning is obvious: Every actuator and a big part of the sensors can be checked individually. So the operability of the controller and the plant components can be proved. A concurrent switch-on of the all actuators, however, is dangerous, because an undetected malfunction of a component could cause damage to the plant, and thus increase the costs and the time of commissioning.

Phase 2 is finished, when all actuators of the real plant are receiving control commands and all sensors triggered mechanically send their status back to the controller.

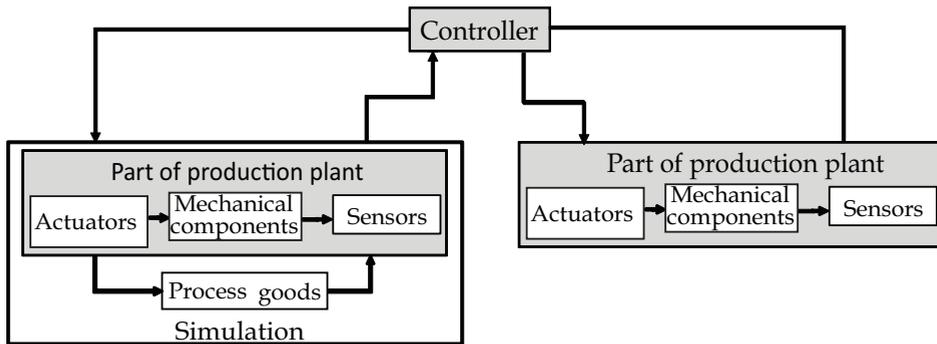


Fig. 7. Phase 2 and 3: Partial Commissioning and Simulation-of-Goods

### Phase 3: Simulation-of-Goods

The Focus of this phase is the Simulation-of-Goods, which is defined as follows. Simulation-of-Goods is the simulation of the good and its behavior, which is processed in a production machine or plant. For simulating the good and its behavior, it is also necessary to replicate the actuators, which influence the good, and the sensors, which are influenced by the good.

The outstanding difference of Simulation-of-Goods to the Hil simulation is, that only these sensors and actuators are reproduced in the simulation system that have direct contact to the good. Operating controls, safety mechanisms, like safety light barriers, automatically closing safety doors, and final position switches, for example, need not to be simulated. The Simulation-of-Goods could be regarded as a real commissioning with simulated instead of real process good. For the Simulation-of-Goods, the models of the Hil simulation could be completely reused.

In this third phase of Hybrid Commissioning, Augmented Reality visualization is very promising. In this case, the process good, as bottles, cars, food, etc., is presented virtually. This virtual process good is then overlaid to the real production plant. The advantage of this kind of visualization is that the interaction between real plant and virtual simulated process good can be monitored ideally. It could be recognized very easy, whenever a process good is positioned directly in the scope of a sensor or an actuator.

The advantage of Simulation-of-Goods is that a big part of the real plant could be commissioned without the danger of damage of the real plant or of the real product by crashes. By this way the waste of production could be reduced as well.

This phase is finished, when the by then integrated part of the real production plant works as demanded.

#### Phase 4: Commissioning of the real plant

Phase 4 of the Hybrid Commissioning is finally the commissioning of the complete real production plant. After checking the operability and correctness of the control unit in interaction with the real plant with the simulated good, the simulation could be disconnected. In this phase, the control unit gets all its sensor signals from the real production plant processing real good, c.f. Fig. 8.

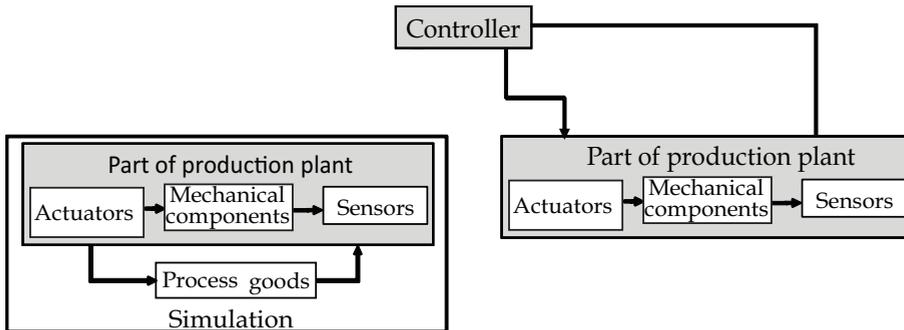


Fig. 8. Phase 4 Commissioning of the real plant

By this procedure, damaging of the production plant and the process good during commissioning can be avoided. This procedure allows a systematic, stepwise commissioning of the mechatronic system without the risk of injuring the operating personnel and of damaging the production plant and the process good. The waste of production and the efforts can be reduced.

## 4. Application of HiL Simulation in the operation phase

By (re-)using HiL Models, modeling efforts can be apportioned. In this section, the advantages of applying HiL Simulation models during the operation phase of industrial production plants are discussed. These comprise the reuse of HiL Simulation models for the purpose of monitoring and diagnostics as well as prognostics and optimization.

### 4.1 Supporting the operation of production plants by simulation

In the operation phase of production plants, the OEE (section 2.1.) can be influenced by several effects, e.g. changing production conditions, improper handling, and delays in the flow of material, abrasion, or even the breakdown of components in the plant. Therefore, condition-based monitoring and machine diagnostics represent an important topic of application and research (Williams et al. 1994). On component-level, several diagnostic functionalities and adaptive control strategies can be applied for detecting and reacting to these influences (e.g. self-tuning, system identification, parameter estimation or state observer approaches) (Isermann, 2005).

Production plants realizing challenging processes, consisting of numerous sensors and actuators, represent complex mechatronic systems. They can be characterized with mainly event-driven behavior. Thus, the application of observer methods from control engineering requires considerable efforts, causes noticeable efforts for modeling, and leads to complex

and specialized solutions. The reuse of already existing simulation models is highly preferable for reducing efforts. In the following sections, methods for realizing monitoring and optimization are discussed.

## 4.2 Monitoring and diagnostics with HiL models

In the operation of production plants, failures in components (like abrasion or defects) can be indicated in marginal deviations of the plant behavior. Identifying these deviations allows to repair or change the component before the failure effects the operation totally, e.g. by break down of components. HiL Simulation models can be used for determining the nominal state of the plant and its components. This enables monitoring and in case of deviations also diagnostics of the plant. Therefore, the HiL Simulation has to run in parallel to the real plant and has to be stimulated simultaneously by the control system. This simulation setup is named Synchronous Simulation.

### 4.3.1 Methodology

The HiL Model of the plant emulates the behavior of the plant on component level or the field floor respectively. It can be used for determining the nominal state of the plant. If the simulation is operated in parallel to the plant, the measurable states of the real plant and of the simulation can be compared and deviations can be detected (Kain et al., 2008; Kain et al. 2009; Kain et al. 2010; Kain & Schiller, 2009). Thus, the signals in the simulation can be used for realizing diagnostics. Furthermore, information calculated in the simulation can be provided to the control system, c.f. as virtual sensor.

For realizing this comparison, different setups can be utilized: In open-loop control systems, variations of output variables do not affect the control system variables directly. As there is no closed loop between the control system and the real system, the control outputs can be applied to the simulation as well. By this approach, the simulation of the plant represents the nominal operation. Deviations detected by comparison of the signals of the real plant with the signals of the simulation indicate disturbances in the real plant.

In closed-loop control systems, variations of control variables directly lead to changes in the controller output. Connecting this controller output to the simulation model does not lead to a nominal operation, if the disturbance is not applied to the simulation as well. Thus, for obtaining the nominal operation in the simulation, the HiL Simulation has to be controlled by a separately simulated or additional hardware control system. Thereafter, the nominal behavior of the simulation with its own control system can be used for comparison with the real plant. These basic concepts are presented in Fig. 9.

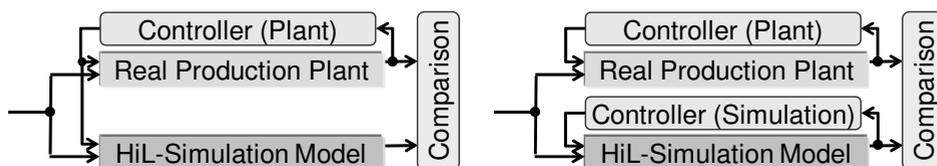


Fig. 9. Basic concepts for Synchronous Simulation

Depending on the level of detail of the HiL Simulation model, different statements can be made. If it comprises the behavior of the plant with its components in detail, the behavior of

the plant according to input signals can be calculated. Assuming the same behavior of the plant and its simulation and an identical initial state, the simulation can calculate the states of the real plant when stimuli are applied to both systems. Stimuli that are not applied to the simulation, but to the real plant and vice versa, lead to deviations that can be detected by comparison of the signals.

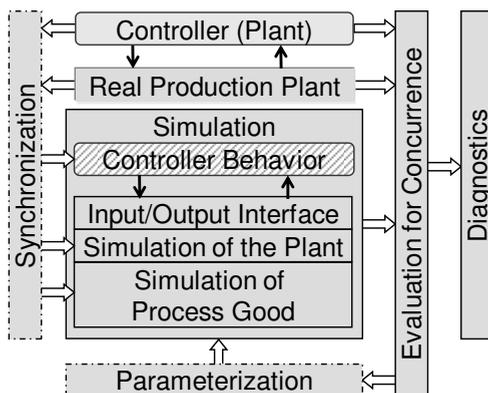


Fig. 10. Simulation architecture realizing Synchronous Simulation

In case of deviations between simulation and real plant, non-intended behavior of the plant can be detected and an appropriate reaction can be initialized. Of course, deviations can also be effected by imprecision of the simulation model.

As the real production plant is available in operation phase, the parameters of the simulation model can be verified easily. Nevertheless, parameterization of the HiL-Models has to be supported. Reducing deviations by stochastic characteristics of the realized process or by average determination of model parameters, deviation between the real plant and the simulation model can be reduced, by adapting the state of the simulation model to measured states of the plant. Thus, an architecture for Synchronous Simulation has to comprehend following parts: mechanisms enabling parameterization of the simulation model, synchronization of the simulation with the real plant and evaluation of the real and calculated behavior, c.f. Fig. 10.

#### 4.3.2 Use cases in Synchronous Simulation

Synchronous Simulation provides knowledge about the behavior and state of the components in the production plant. It enables the online monitoring of the production plant and diagnostics of faults. Condition monitoring is defined as continuous or periodic measurement and interpretation of data for indicating the condition of an item to determine the need for maintenance (BS, 1993).

Dealing with production plants, condition monitoring can be detailed in Component Monitoring and Process Monitoring (Weck, 2001). In Component Monitoring, the components of the production plant are analyzed. The objective is the identification of faults in the components, before failures in the production plant are caused. For receiving

information about the components, this method in general requires sensors mounted directly to or stimulated by the monitored components, e.g. (Christer & Wang, 1995).

In contrast, Process Monitoring focuses on the analysis of the production process realized in the plant. The objective is to analyze, whether the process fulfills the requirements. Usually, information about the process is received by sensors in the plant stimulated by the process.

#### *Component Monitoring*

Realizing component monitoring requires information about the current state of the component in regard of the monitoring goal (availability, life period, current state, current dynamics ...). Depending on the complexity of the component, this can be realized by measuring the required data in the real component, if it is equipped with sensors.

If there is no data available, e.g. if the real component is not equipped with adequate sensors, it is possible to gain the information required by Synchronous Simulation. Therefore, the HiL Model of the component is connected to the plant and stimulated by the real signals in Synchronous Simulation. Representing the behavior of the real component (functional, timing, communication) the state of the HiL-component represents the state of the real component. Thus, the required information can be measured in the HiL Model. For realizing sophisticated Component Monitoring functionality, the functional behavior of the HiL model can be extended for providing the required information. Exemplarily, gaining information about energy consumption or friction in a real component might be very costly due to additional sensors or accessibility of the signal values.

#### *Process Monitoring*

Hybrid Commissioning requires the HiL Model to represent the component behavior and the flow of material. This characteristic also enables Process Monitoring.

Therefore, the HiL Model, representing the functional and timing behavior and the communication interface, connected to the real plant is stimulated by the real control system. Representing the chain of effects (actuators, flow of material, sensors) the calculated sensor signals can be compared with the real measured signal values.

This enables the online monitoring of the production process realized in the production plant and diagnostics of process faults. Therefore, the behavior of the realized process has to be analyzed, whether it is within the boundaries calculated by the simulation.

Reusing HiL Models in Synchronous Simulation enables monitoring and diagnostics of the production plant. Providing information about the state of the components, the HiL models enable Component Monitoring. Extending the models, e.g. with dynamic attributes, allows comprehensive conclusions about the components in the plant, e.g. energy consumption. Representing the flow of material, the HiL models enable Process Monitoring. Furthermore, information about the components and the process can be processed on the control level of the production plant for sophisticated control strategies.

## **4.4 Forward Simulation**

Many influences to the production plant during the operation phase were presented above. If influences are determined to be systematic, their effect on the OEE of the plant can be predicted by simulation, e.g. changing production conditions, or delays in the flow of material. Additionally, if the control system was optimized in the engineering phase according to assumed process parameters divergent from the current situation, changes of the parameters in the control system can improve the plant behavior. Therefore, the models of HiL Simulation can be applied predicting the behavior of the controlled plant, called

Forward Simulation (Kain et al., 2008; Kain et al. 2009; Kain et al. 2010; Kain & Schiller, 2009).

#### 4.4.1 Methodology

The behavior of the controlled plant consists of the functional behavior of the plant, represented by the HiL Models, and the behavior of the controller, represented by a model of the controller. Validation of the simulation results can be realized by comparison with the real plant behavior. This enables a detailed predictive simulation, called Forward Simulation, cf. Fig. 11.

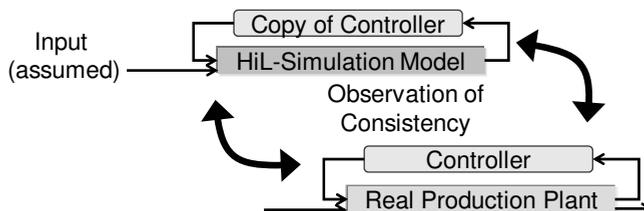


Fig. 11. Concept Forward Simulation

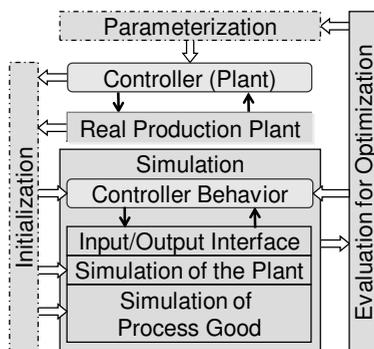


Fig. 11. Forward Simulation: concept and simulation architecture

Optimizing the control system offline based on verified HiL Simulation models representing the behavior of the plant in detail offers several advantages: In a first step, the optimal parameters can be determined based on simulation experiments with diverse constraints without influencing the real plant. This process can be repeated time or event triggered.

In a second step, the control system can be adjusted to the parameters and the optimized control system can be applied to the real plant consequently. Thereby changes in the control system might range from simple parameterization to adaptation of the controller software.

The basis for this optimization is a HiL Simulation model of the plant representing the behavior of the real plant and a control system. In addition to Synchronous Simulation, this simulation approach requires mechanisms for parameterization of model parameters and mechanisms for evaluation of the simulation results. The Forward Simulation is initialized with the current state of the plant and the controller. For predicting the behavior, inputs

applied in the future to the production plant and optimization parameters could be considered as well, if available. The resulting architecture of Forward Simulation is presented in Fig. 11.

Due to restrictions of real hardware controllers, this can be only realized by means of a simulation of the controller behavior. The HiL Simulation has to be detailed sufficiently to enable the evaluation of application specific optimization criteria.

#### **4.4.2 Use cases Forward Simulation**

Many applications exist for applying simulation methods in the operation phase of production plants. Besides production planning issues and supporting the production planning and control, also detailed functional models are applied in the ramp up and the prediction of production capability. In the following, these use cases are presented and compared.

##### **Ramp up**

The efficient ramp up of industrial production plants poses a big challenge due to short product life cycle and numerous product variants, e.g. in automotive industry. For economic reasons, the production process should be operated at the desired production rate and output as soon as possible. After commissioning the plant, e.g. by Hybrid Commissioning, there are still adjustments necessary. Therefore, in (Lanza & Fleischer, 2005) an approach is discussed, supporting this adjusting process with an extended functional simulation of the production plant. Therein, the capability of producing products with components of plant is modeled. This enables the prediction of the product quality in the plant by different action alternatives. Thus, the best action alternative can be chosen and applied to the plant.

Depending on the size of the simulated production plant and the expected simulation results, the level of abstraction of the simulation model has to be chosen. In case of detailed conclusions about significant parts of a production plant, reusing the functional part of HiL-models and functional control logic can represent the behavior of the plant sufficiently.

##### **Forecast simulation**

Predicting the plant behavior is very important for production planning and control. Thus, there exist many simulation systems, providing information about the plant behavior in different levels of detail. (Hotz et al., 2006) discuss a system in automotive industry, predicting the behavior of large production plants/production factories. Therefore, the basis is a simulation model, representing the in-firm logistic and the production times and capacities of parts in the production factory in discrete event models. Initialized with the current state of the production plant (allocation of material, future orders), the quantity produced in a time horizon in the future can be calculated. Also, conclusions about the influence of cumulated lags and dynamic behavior of storages can be analyzed. Another application of forecast simulation is the support of the detailed production planning and control. In case of identified need of action, the best action can be chosen by calculating the effects on the plant behavior.

These applications require predicting the behavior of the controlled plant. Thus, models representing the controlled behavior of the components in the plant are required. Due to the rough level of detail required in this use case, detailed HiL Simulation models are not appropriate, but discrete event representations might be suitable.

**Forward Simulation**

Detailing the simulation model representing the functional and timing behavior of the components in the plant and the control logic, enables Forward Simulation. Therein, the models of the components represent the uncontrolled behavior. For representing the model of the controlled plant, also the behavior of the control system has to be considered.

This detailed model of the production plant enables the calculation of the plant behavior on process level. Including the signal flow between the components and the controller enables the detailed analysis of the plant behavior on signal level. Consequently, conclusions about the behavior of the components on process level are possible (Kain et al., 2010; Kain & Schiller, 2009).

This simulation model requires the representation of the functional and timing behavior of the components in the plant. Depending on the model of the control system, the communication interface has to be defined.

In Fig. 12, the discussed use cases are arranged according to the criteria level of component detail and size of the focused plant. The use case Forward Simulation requires the most detailed models of the components in the plant and focuses the most restricted part of the production plant. In contrast to the presented use cases of Forecast Simulation, Forward Simulation is suitable for reusing HiL-Simulation Models in the operation phase of industrial production plants for prediction and optimization of the plant behavior. This approach provides detailed information about the components and the process on field floor level.

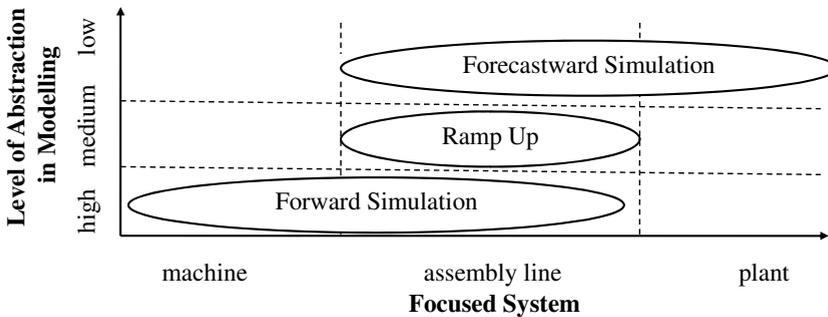


Fig. 12. Overview simulation methods for prognostics

**5. Showcase realization**

In this section, the application of the presented concepts is shown in practical use. Thereby, a demonstrator for production plants represents all characteristics of a real production plant.

**5.1 Hybrid Commissioning**

The application of Hybrid Commissioning poses some challenges. As described before, it is required that the simulation of a plant and the plant itself run in parallel. Moreover, it is necessary, that control commands could be sent to the real and the simulated actuators at the same time, and that single sensor signals could be taken either by the real or the simulated plant without big efforts of reconfiguration. Hence, Hybrid Commissioning is based on forwarding and redirecting of signals; either sensor signals to the controller or

actuator signals from the controller. It is also a requirement that the original controller interface is used. If the controller communicates with the plant, i.e. the sensors and actuators via a field bus, then this interface must be used for the Hybrid Commissioning as well.

The type of interface has a significant impact on the actual realization of Hybrid Commissioning, and so its realization cannot be generalized. As an example, however, a realization of PROFIBUS DP driven production plants is given. Anyway, the realization could also be achieved with other communication technologies like Profinet, EtherCAT, CAN (Thomesse, 2005) or Flexray (Froschauer & Auinger, 2009).

Fig. 13 shows a simplified system architecture of Hybrid Commissioning for a plant, which communicates with the field bus PROFIBUS DP. In this example, a Programmable Logic Controller (e.g. with bus address 1), is connected to a real decentralized input-output periphery (e.g. with bus address 13), and its simulated counterpart. To be able to fulfill the mentioned requirements, a so called Merge-Tool is necessary. This Merge-Tool is interconnected between the controller and the real and the simulated plant components, which act as slaves according to the Master-Slave principle in case of PROFIBUS DP.

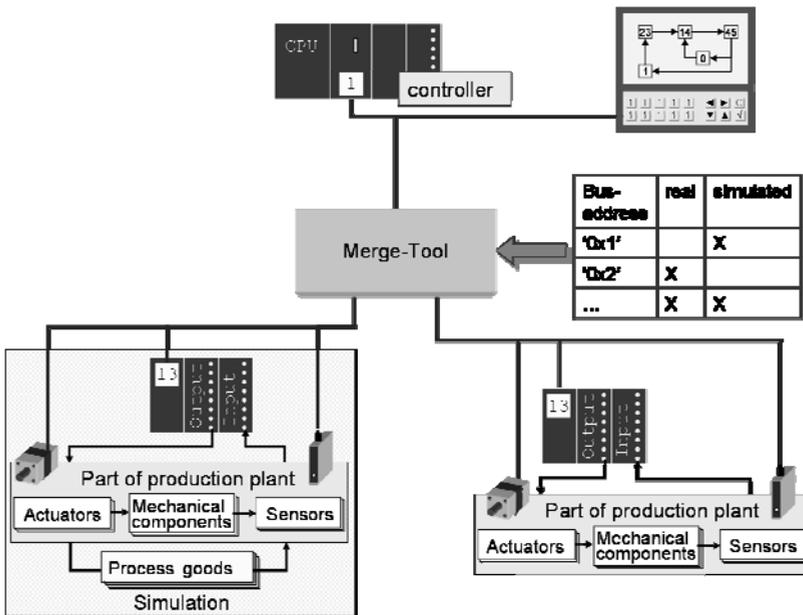


Fig. 13. System architecture with Merge-Tool

The main purpose of the Merge-Tool is to control the execution of Hybrid Commissioning, i.e. the Merge-Tool determines the forwarding and redirecting of signals and hence determines the phase of Hybrid Commissioning. Via the Merge-Tool, the real actuators are activated and step-by-step the real sensor signals are taken into the control-loop.

The Merge-Tool has, however, some more tasks that are rooted in the characteristics of the field bus PROFIBUS DP. PROFIBUS DP is a reliable field bus that detects several errors, like transmission errors or unwanted multiple devices with the same bus address. Adding a

simulation system to the real system (consisting of controller and plant) and changing signals that are transferred via the field bus would generally lead to an interruption in the PROFIBUS communication. Thus, additional task of the Merge-Tool is to keep up the field bus communication, despite additional bus components and changing of bus signals.

The tool has the task to merge the real slave and its simulated counterpart for pretending the master (controller) the existence of only one slave.

In case of PROFIBUS DP, the communication between master and slave can be divided into two parts. One part consists of the master-requests, i.e. the polling of the slaves by the master. The other part consists of the slave-responses, i.e. the responses from the slaves to the master. Master-requests are telegrams which are transmitted from the controller to the slaves. These can be telegrams for parameterization and configuration, commands to actuators or telegrams for polling the sensors. The Merge-Tool has to duplicate or copy these telegrams, respectively, in order to send them to the real and to the simulated slave. Therefore, a main aspect of the Merge-Tool is the copy functionality.

Another aspect of the Merge-Tool is to process the slave-responses. For Hybrid Commissioning, both simulated and real slaves, send telegrams to the master. However, the master can only handle one telegram for each bus address. Thus, the Merge-Tool has the task to merge real and simulated telegrams and forward new composite telegrams to the master. This is the primary purpose of the Merge-Tool, as for Hybrid Commissioning, sensor data from the real plant as well as sensor data from the simulated plant should be provided for the controller. For example, from a peripheral with 8 bits input, 4 bits should be taken from the real plant and 4 bits should be taken from the simulation. This pivotal merge-functionality led to the name Merge-Tool.

Hybrid Commissioning has so far been implemented in several demonstrators. An example of such a demonstrator is illustrated in Fig. 14. This demonstrator consists of a bottling plant, which fills up little bottles, a HiL Simulation and a control unit. Additionally, the Merge-Tool can be seen, which is interposed between the controller, the real production plant and its simulated counterpart. The bottling plant consists of four separate stations which are controlled by programmable logic device Siemens SIMATIC S7 317-2 DP and connected via PROFIBUS DP communication decentralized peripheries Siemens ET200M, to which several actuators, like driving motors, and sensors, like light-barriers, are connected.

The HiL Simulation (functional and timing behavior) of the production plant is modeled with the simulation tools Siemens SINUMERIK Machine Simulator. As the real components are connected to the controller via Profibus DP, the communication interface of the simulation is realized by SIMBApro, an interface card for Profibus communication. The Merge-Tool copies the control commands and sends them, depending on the actual configuration, to the real production plant, to the simulation, or to both of them. According to the configuration, either simulated or real sensor signals are sent back to the control unit.

The Merge-Tool has so far only been developed for PROFIBUS DP driven production plants. However, a similar device that can handle other field bus systems or point-to-point connections could be (easily) developed as well. The Merge-Tool can be reused for every other PROFIBUS DP driven plant and just needs to be reconfigured for each use case. So, Hybrid Commissioning can be considered as a very powerful and low cost approach by reusing existing Hil models.

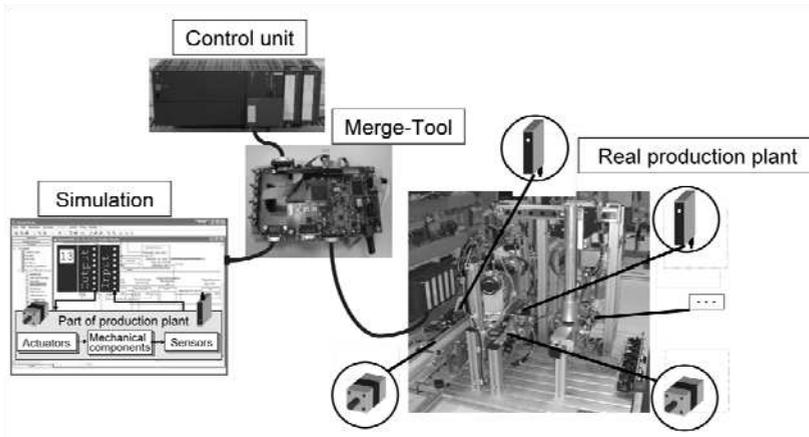


Fig. 14. Demonstrator for Hybrid Commissioning

## 5.2 Synchronous Simulation

First, background for the application of Synchronous Simulation is discussed, and then the application to a demonstrator for automation systems is presented. Monitoring with Synchronous Simulation requires accurate simulation models. Assuming a constant behavior of the components, the parameters of the HiL models can be determined by established verification and validation techniques, e.g. (Sargent, 2007).

In the case of shifting component behavior, as induced by abrasion, the parameters of the HiL models have to be adapted for representing the behavior of the real component furthermore. Compared to observer methods in control engineering, deviations between the real and the simulated component have to be considered in parameterization of the HiL-model. Depending on the characteristic of the modeled component, this can be realized by many algorithms, ranging from simple PID feedback to sophisticated optimization algorithms, c.f. e.g. Kalman filter in control engineering (Nise, 2006). As a result, the parameters of the HiL-models are adapted over time to represent the behavior of the real component in a best manner.

In a demonstrator scenario, the Synchronous Simulation model of the system and the process is built up from HiL-models. The simulation model contains the sensors and actuators of the demonstrator as well as the realized technical process of gripping and moving bottles.

The signals between the plant and the controller are available via a PROFIBUS DP slave emulation with Siemens Simba Pro. The control signal of the real controller is input for the Synchronous Simulation of the system, cf. Fig. 15.

The simulation tool Sinumerik MS enables the programming of user-specific functions in a simplified version of the programming language C. The monitoring and analyzing units are also implemented in the simulation tool Siemens Machine Simulator. Therein, the output signals are calculated and compared to the real output signals. Therefore, detected deviations are analyzed and compensated on signal level in the parallel HiL Simulation. The monitoring components include the in- and outputs of both simulations and the real system. The diagnostics component enables the analysis of deviations.

In the scenario presented, component monitoring is possible by tracing the state of the actuators in the simulation. In case of exceeding defined limits, the controller of the plant is informed by the field bus interface card.

Process monitoring is realized by comparing the signals of the real sensors and the calculated sensors in time and value. For reducing the propagation of deviations, application specific intervals are defined for synchronizing the simulated flow of material with the real one permitting discrete synchronization.

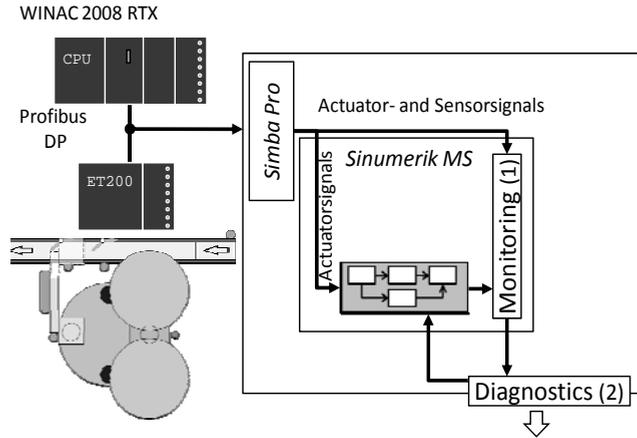


Fig. 15. Framework for simulation based monitoring and diagnostics for hybrid automation systems.

### 5.3 Forward Simulation

For representing the nominal behavior of a closed-loop system in the Forward Simulation, the simulation system has to fulfill certain requirements:

- Consideration of the behavior of the controller, e.g. by proposing an additional controller simulator. Depending on the chosen controller model, interfaces to a platform, executing the controller code, are necessary.
- For receiving simulation and optimization results in-time before appearing in the real plant, the simulation models must be executed faster than the reality.
- Discrete-Event-Systems can be calculated quickly, when only few events occur in the system. Therefore simulation velocity depends on the modeled behavior. This poses the challenge to consider the behavior of the real operating controller.
- The Forward Simulation is started periodically for evaluating the influence of changing production constraints. Thus an initialization method transferring the respective state of the controller and the plant to the simulated controller and the HiL Simulation is required. Therefore, a real-time simulation-plant interface has to be available.
- After evaluating the simulation result according to optimization criteria, the behavior of the real controller has to be adjusted, e.g. by parameterization.

The reuse of HiL Simulation models for Forward Simulation was applied for optimization issues. First, a software realization is discussed, then the application to a demonstrator for automation systems is discussed exemplarily.

Forward simulation requires calculating the behavior of the plant before it happens in the real plant. Afterwards the behavior is evaluated and interventions to the plant are derived. Therefore, the Forward simulation reuses the functional and the timing behavior of HiL Simulation models, the communication interface might be neglected.

In the following, a software realization is presented, which executes the HiL Models in an event discrete simulator. Therein, the communication interface of the models is reduced to the in- and outputs of the components. This enables a rapid calculation of the plant behavior and enables the application of different optimization strategies.

Forward Simulation is realized in a software framework, c.f. Fig. 16. Industrial software tools were integrated to the framework for reducing integration efforts in the industrial engineering flow. The behavior of the plant is calculated in Siemens Plant Simulation. The models represent the functional and timing behavior of the HiL Simulation models. For considering the behavior of the controller system, Siemens PLCSim is integrated. This enables the reuse of the original controller code. Obviously, also an abstraction of the controller code could be used. Depending on the representation of the controller code, an execution environment has to be chosen and integrated. For efficient calculation of the system behavior, the time-discrete behavior of PLCSim is encapsulated for event-discrete calculation. This enables the efficient event-based interaction with Plant Simulation.

Initialized with the state of the real plant (consisting of the plant, the controller system and expected production orders), this setup enables the rapid calculation of the system behavior. The evaluation of the system behavior is realized in Mathworks Matlab. This enables the application of several optimization strategies adapted to the plant characteristics.

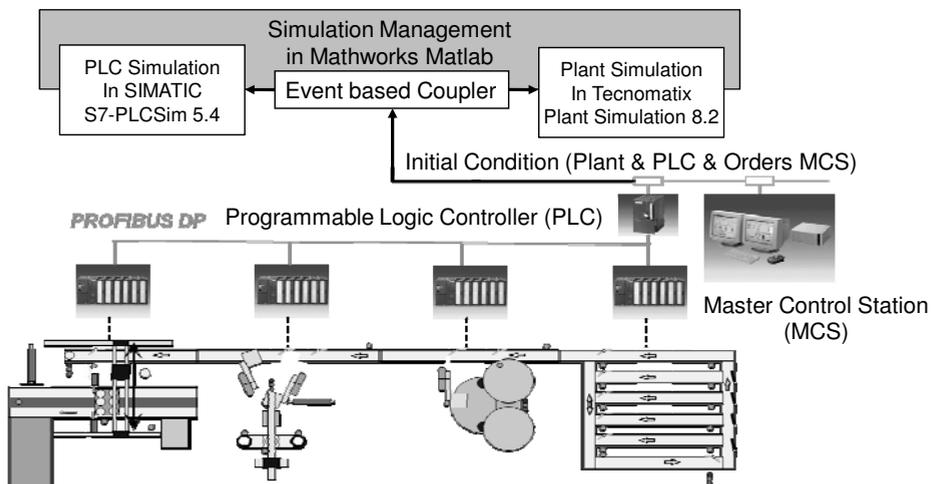


Fig. 16. Framework for Forward Simulation

Based on a first shot calculation, the system behavior is evaluated according to the chosen criteria. These might include production time, energy consumption or the abrasion of components.

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## 6. Conclusion

HiL Simulation is a very well known method that is applied during the engineering phase of mechatronic systems. By definition, a HiL Simulation is a system that consists of real hardware components and simulated components that are connected to each other and show a (closed-) loop character. In Automation Industry, HiL Simulation is typically applied in the development phase of the lifecycle of industrial production plants. In this chapter, the authors proposed the reuse of HiL Simulation Methods in the commissioning and the operation phase by the applications Hybrid Commissioning, Synchronous Simulation and Forward Simulation.

Hybrid Commissioning is a stepwise procedure starting from a simulated production plant to a real production plant. By this approach, it is possible to reduce the danger of damages at the process of commissioning. At the same time, the commissioning phase could be passed more systematically, and so the partially high efforts of commissioning could be reduced.

For increasing the benefits of HiL-Models, a methodology for supporting the operation phase of industrial production plants has been proposed afterwards. Synchronous and Forward Simulation enable monitoring and diagnostics as well as prognostics and optimization based on reused HiL Simulation models.

Obviously, the quality of the Synchronous Simulation is suitable to allow conclusions about the states of the plant in component and process monitoring and diagnostics and can strongly support the control system of the plant by providing virtual sensors. The Forward Simulation enables the optimization of the control system due to varying operation conditions. Mechanisms for synchronization with the real plant enable efficient modeling of the Synchronous Simulation, whereas the Forward Simulation demands for detailed modeling and for robust criteria for evaluation respectively.

It was shown that each of these approaches can easily be implemented and that a (re-)usage of HiL Simulation models in different phases of plant lifecycle can increase their benefits. The insertion of the proposed approach showed that it could be successfully used in industrial applications and hereby decreases the efforts in the commissioning and the operation phase of industrial production plants.

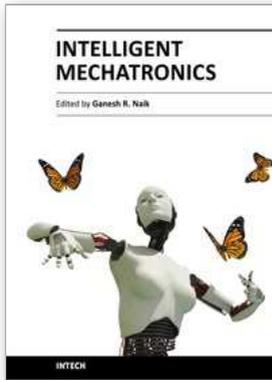
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This book is intended for both mechanical and electronics engineers (researchers and graduate students) who wish to get some training in smart electronics devices embedded in mechanical systems. The book is partly a textbook and partly a monograph. It is a textbook as it provides a focused interdisciplinary experience for undergraduates that encompass important elements from traditional courses as well as contemporary developments in Mechatronics. It is simultaneously a monograph because it presents several new results and ideas and further developments and explanation of existing algorithms which are brought together and published in the book for the first time.

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Slavka Krautzeka 83/A  
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Unit 405, Office Block, Hotel Equatorial Shanghai  
No.65, Yan An Road (West), Shanghai, 200040, China  
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元  
Phone: +86-21-62489820  
Fax: +86-21-62489821

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