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Agile scheduling and control for industrial product-service systems

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Abstract

An Industrial Product-Service System (IPS²) is characterized by a high integration of product and service shares. This implies that the providing company develops an IPS² consisting of product share, e.g. a highly complex precision machine tool, and service share to increase customer value, strengthen the relationship between customer and provider and finally generate profit. However, providing an IPS² involves a high degree of organizational effort. The operation of an IPS² includes the detection of service demands, strategic and operative scheduling of processes and resources, coordination of service and supply network partners and the monitored delivery of service processes.

In this paper, an IPS² Control Architecture for the operation phase is proposed. Then, the function and application area of two software systems, the IPS²-Execution System and the IPS²-Control System, are described and their interaction within the proposed architecture is outlined. Furthermore, the detailed interaction process is illustrated in an application scenario in order to demonstrate the advantages and necessity of both systems and their interdependency. Also, an outlook on further research is given.

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1. Introduction

An industrial product-service system (IPS²) is characterized by a high integration of product and service shares. This integration implies that the providing company develops an IPS² consisting of product share, e.g. a highly complex precision machine tool, and service share to increase customer value, strengthen the relationship between customer and provider and finally generate profit [1]. However, providing an IPS² involves a high degree of organizational effort. Development of adequate business models, engineering of IPS² and support of the operation thereof are some of the challenges IPS² providers are confronted with.

When looking closer at the operation phase of an IPS², the detection of service demands, strategic and operative scheduling of processes and resources, coordination of service and supply network partners and the monitored execution of delivery processes has to be

managed. A system which fulfills this function in the field of the precision machine tool industry will be introduced and illustrated with a control loop analogy.

2. State of the Art

To create a basic understanding for IPS² operation, the topics of IPS² itself, IPS² organization and planning and IPS² condition monitoring and service process support will be introduced.

2.1. IPS²

In [1] an enhanced definition of IPS² based on [2] is given:

“An Industrial Product-Service System is characterized by the integrated and mutually determined planning, development, provision and use of product and service shares including its immanent software components in Business-to-Business applications and

represents a knowledge-intensive socio-technical system."

IPS² aim at fulfilling contractually defined customer needs by the provision of product as well as service shares. To be able to guarantee a contracted business model [3], delivery processes are developed, planned and executed. Delivery processes can be maintenance procedures, technological upgrades, spare part deliveries or even training courses. Each of the delivery processes has requirements that have to be fulfilled by resources. These resources can be provided by a network of partners as well as by the provider or the customer. Hence, for the operation of IPS², the organization of networks and the planning methods need to be executed.

2.2. IPS² organization and planning

The organization needed for providing IPS² is a layered network structure. The provider can use third party suppliers and resources of the IPS² customer to ensure the operation of an IPS². The provider and all his suppliers form the Provider Network (PN) [4]. With the methods of strategic capacity and operational resource planning for IPS², IPS² networks are formed [5]. They consist of all partners that take care of a specific IPS². The IPS² network includes the customer of the IPS² as well. For each delivery process that is executed, an IPS² delivery network (IPS² DN) is instantiated. Only partners involved in the execution are involved in the IPS² DN [4].

Strategic capacity planning is used to determine the capacities needed to supply all IPS² of a provider. Capacities of all kind of resources like humans, spare parts and tools are taken into account. The result of the planning is a delivery plan for all IPS². It contains a schedule for each delivery process to be executed and the assignment of resources to delivery processes [5].

Whenever an unplanned incident occurs at one IPS² which requires a new delivery process to be planned, operational resource planning is used. The available resources are redistributed and the delivery schedule adjusted to provide the new delivery process for one IPS² while not affecting the operation of other IPS². Both the strategic and operational planning methods can be implemented using an genetic algorithm [5].

Network management for IPS² as well as planning has to be carried out by the IPS² provider. To support him in performing these tasks, a software tool fitting his needs can be used. An IPS²-Execution System (IPS²-ES) can provide the required functionality. Using cloud computing, the task of planning capacities and resources for several IPS², possibly hundreds, can be executed in real time. The closely connected management of the network is supported by using an open architecture inside the system [6]. Especially information about

planned delivery processes and resource availability has to be exchanged.

2.3. Condition monitoring and service process support

The automation of the operation of an IPS² aims at the control of processes in both product and service shares. On product share side, these processes can include condition monitoring of critical components [7], tools [8] or the automated execution of service related machine routines [9]. On service share side, the processes include human processes such as diagnosis or spare part exchange. The closed-loop control of such human processes is established through interactive instructions for a service technician with an adaptive workflow sensitive to the actual state of the product share. An IPS² process can include several involved actors on product as well as on service side.

An agent system therefore provides means to represent all actors involved in IPS² operation and to execute such necessary processes [10]. The agent paradigm is founded on the view of a system as a computational organization consisting of various interacting roles [11]. The machine tool, individual components or consumable parts such as milling tools can be subject to monitoring, for example if their availability is guaranteed in the IPS² contract. Also each party involved in the IPS² operation is represented by a software agent to ensure the automated communication between these partners.

The advantage of this agent-based IPS² control system is the flexibility of reacting to changing business models and service network partners. Furthermore, the complexity within one technical system consisting of many components can be handled in an efficient manner. Lastly, the shared definition of an overall concept in terms of a common ontology facilitates the agent communication and the long term data processing leading to an externalized knowledge representation.

3. Proposed Concept for IPS² Control

A machine tool sold and operated as an IPS² is characterized by a high integration of product and service shares. This implies that product and service share can be substituted if they have the same function or sub function in terms of fulfilling a customer need. During operation, the provision of service shares require that organizational efforts are undertaken in order to fulfill a contracted degree of service (e.g. availability) in an economically feasible way. A complete automation of necessary processes seems desirable in this context, but is highly challenging due to the vast multitude of uncertainties that had to be considered. This especially applies to the manual processes that become necessary

on site of the product share. Looking at the current state of the art in planning, execution and documentation of engineering services and their great potential for rationalization, these challenges need to be overcome in order to assure an efficient, secure and high quality operation of IPS².

The proposed approach encapsulates tasks necessary for the IPS² delivery and treats them as control problems. By pursuing this approach, a partial automation of processes shall be reached. Parts of the processes that require the manual execution of tasks are considered analogously.

The fact that an IPS² is a dynamic system that requires continuous effort of the IPS² provider is inherent in its definition [1], [2]. These circumstances already lead to the representation of an IPS² as a control loop in the development phase [12]. However, in order to control an IPS² including its product and service shares during the operation phase, further aspects have to be considered and the control loop has to be extended to this phase of the lifecycle. Therefore, an IPS² Control Architecture is proposed.

3.1. Design of an IPS² Control Architecture

An IPS² can be considered a Large-Scale Complex System: it is composed of a number of smaller constituents which serve particular functions, share particular resources, governed by interrelated goals and constraints and require more than one controller [13]. Controlling these kinds of systems, there are different approaches, which all aim at the reduction of complexity. From purely hierarchical multilevel systems, which allow the circulation of feedback only along the vertical axis, a development towards *heterarchical* concepts emerged [14]. Heterarchical control schemes allow the horizontal exchange of information among different control units on the same level, providing means for cooperation.

Looking at the abovementioned challenges in IPS² operation, an IPS² fulfills customer needs by providing a specified degree of performance. This level can be expressed in contractually defined parameters, e. g. in terms of availability or quality of output parts.

In order to provide the degree of performance agreed upon during the operation phase, the IPS² has to be influenced on various levels depending on its current state.

3.1.1. IPS² Control Model

During its operation, an IPS² can be influenced on several levels. In the framework of this paper, these levels are distinguished as follows:

1. Lifecycle level

2. Operation level
3. Process level
4. Effect level

IPS² operation on each of these levels is considered as a closed-loop control system (Figure 1). A closed-loop control system generally consists of controller, actuator, controlled system and measuring unit (see Figure 1 on operation level). Through a continuous measurement of the controlled system, its deviation from the command variables is assessed in the controller. A decision is made in the controller on basis of the deviation and a correcting variable is passed on to the actuator, which imposes a correcting effect in the controlled system. Subsequently, the controlled system is measured.

Higher level control loops determine the goals of the lower levels, resulting in command variables. Thus, all levels mutually affect each other.

Lifecycle level

The Lifecycle level contains the contract definition for and the development of the IPS². Based on the customer demands, the business model is created and an adequate IPS² product model developed and implemented. The IPS² is then continuously evaluated regarding its fulfillment of customer needs and possible deviations from the defined goals are reacted to with adaptations of the business model. Newly arising or changing customer demands can be covered by business model adaptations. According to the changes, the IPS² product model is adjusted. By these means, the overall customer value is maintained throughout the IPS² lifecycle. The control loop has a time horizon of several days to weeks.

Operation level

Looking at the operation in greater detail, the Operation level provides the basis for ensuring required command variables. These are defined as IPS² target values, in order to determine the level of performance for the IPS² operation. A target value could be the Overall Equipment Effectiveness (OEE), or individual factors of the OEE equation. The desired influence on these values is achieved by strategic and operational planning of delivery processes and the consideration of process requests due to unplanned demands.

Based on the IPS² product model, the initial delivery plan consisting of delivery processes is created with the strategic capacity planning method. The continuous monitoring of relevant machine and operational data on Process and Effect level measures the actual IPS² performance parameters. These parameters are then compared with the target corridors and allow the detection of any deviations.

Such deviations indicate new and often unforeseen demands. The operative scheduling of processes with

available resources is necessary to fulfill these demands. The needed type of process has to be available in the IPS² product model in order to be scheduled automatically as a response to the demand. The adequate process is selected by the IPS²-CS. Based on this selection the process is included in the updated delivery plan. If no suitable process is available in the product model, the demand for a new process is escalated to the Lifecycle level. The consequence would be a reconfiguration of the IPS² business model. The Operation level has a time horizon from several hours to several weeks.

Process level

For each of the deployed processes of the delivery plan, a closed-loop control is established on the Process level. The whole solution space of possible process steps including available alternatives is defined in a so-called process network. Utilizing the inherent flexibility of these process networks, the optimal sequence of process steps will be adapted to the actual situation according to the closed-loop feedback.

Recognized symptoms are transformed into possible goals and lead to a decision about which process step to choose next. The aim is to execute the overall process in the most effective way. Whenever it is not possible to reach the goal with the range of available process steps,

an additional delivery process has to be scheduled on the Operation level. The Process level has a time horizon ranging from hours to minutes.

Effect level

Each concrete process step is controlled on the Effect level by influencing the system and monitoring the result. Both the product share (the technical system) and the service share (the service activity) are controlled interdependently. The Process level has a time horizon ranging from milliseconds to minutes, depending on the type of effect to be obtained.

For the technical system, the influence is obtained automatically, either through actuators or the changing of intrinsic system variables. Means of condition monitoring are applied in order to track each action. Depending on whether the intended effect was achieved or not, appropriate measures can be taken as a reaction. The operations on this level therefore come closest to the conventional, technical understanding of a closed-loop control system.

On the service side, the influence is achieved by multi-modal instructions for the personnel providing the service process [15]. The monitoring of the action can be realized by directly tracking the human activity [16] or the effect on the technical system by the monitoring function of the IPS²-CS.

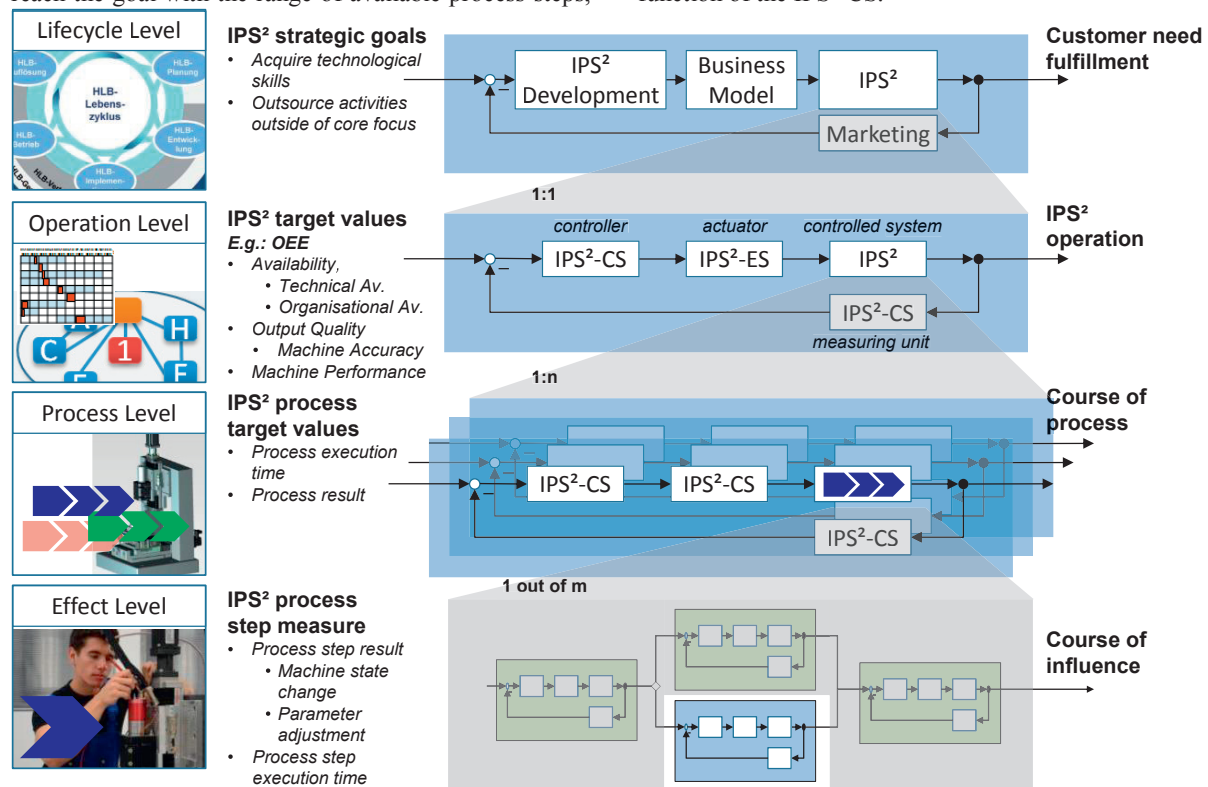


Figure 1: Levels of the IPS² control architecture (IPS²-CS = IPS² Control System, IPS²-ES = IPS² Execution System)

When an inappropriate action or effect is detected, according instructions are issued.

The interdependencies between product and service share which exist in an IPS² are visible on the Effect level and express how the IPS² control architecture can utilize both to reach an effect. However, when the intended effect cannot be achieved with the selected process step, an alternative step has to be selected on the process level.

All levels are connected through the consistent goal, from which the command variables on all levels are derived. Also the abovementioned escalation mechanisms provide means for transfer of control towards a higher level to expand the solution space in order to deliver the contractually defined customer value. While the control on the process level and the Effect level is executed for one specific IPS², the Lifecycle levels and the Operation levels of different IPS² are interconnected and have a wider range of influence. On the Lifecycle level, features and processes are developed for one specific customer, however, the results can be used to design and implement an IPS² for another customer. On the Operation level, processes for multiple IPS² are planned centrally, but the request for including a process for one IPS² in an updated delivery plan is issued by each IPS² independently.

On all levels, data has to be collected to provide an information basis for new developments or changes of IPS². Among this data are the command variables, the control factors, the control variables and the measured variables. Based on knowledge that can be derived from this data, the control on the Lifecycle level, especially the design and implementation phases for an IPS², retrieves new input for a better fulfillment of customer needs.

In the following, the focus is set on the Operation level of the IPS² control architecture. On these levels, the existing methods developed for the management of delivery networks, the planning of capacities and resources as well as the control of process steps will be set into context accordingly. Through the connection of these systems, the core of the IPS² Control Architecture will be established.

4. Operation Level in Detail

On the operation level, the agent-based IPS²-Control System (IPS²-CS) is considered as the controller (Figure 1) and the IPS²-Execution System (IPS²-ES) as the actuator. They determine what influences have to be exerted in order to keep the IPS² as the controlled system in Figure 1 in stable operation. The monitoring component of the IPS²-CS is the measurement unit and ensures the closed-loop control by providing the data the

IPS²-CS needs to make a decision. The decision is submitted to the IPS²-ES in order to become effective.

Looking closer at this functional behavior, we first have to understand which decisions can be made for what reason by the IPS²-CS. The following example is given: A micro machine tool is operated in an availability-oriented business model: Therefore, critical components are subject to monitoring. The IPS² solution space offers delivery processes for keeping up the availability. Therefore, a plan with scheduled delivery processes is in effect.

During the manufacturing operation, a critical state of the spindle is reached and detected by the monitoring component of the IPS²-CS. Because a failure of the component would affect the availability of the whole machine, the IPS²-CS decides that a spindle exchange is required. The spindle exchange process is defined in the IPS² product model and has several requirements regarding human resources (skills), tools and spare parts. The IPS²-CS also derives the urgency of the process from the monitoring data, e. g. the actual availability of the IPS². Because the availability is guaranteed to be above 95%, and the actual value in this example is above 98%, the criticality is considered medium. Subsequently, this data is submitted to the IPS²-ES.

The IPS²-ES retrieves data about the required process from the IPS² product model. The default time window could be 72h. Thus, the individual time window is calculated. The calculation is based on the default time window given by the process description and the criticality provided by the IPS²-CS. For this example, the actual time window could be adjusted to 48h.

The process including the generated time window information is then included in the delivery plan and the planning algorithm is executed to optimize the delivery plan. The scheduled downtime of the machine given by the IPS² customer is taken into account during this step. This determines, at which time the process is actually executed and which resources are utilized. The new delivery plan is then passed on to the IPS²-CS.

In this example, the requirements for the interfaces between the IPS²-CS and the IPS²-ES are clearly visible. The first interface needed has to be designed for information transfer from the IPS²-CS to the IPS²-ES. Through this interface, data about a required process and its urgency is transferred. The information has to be consistent throughout both systems. Therefore, the IPS² product model has to contain an individual ID for each available process for reference and IPS²-CS and IPS²-ES have to agree on a domain for urgency. Based on this urgency domain, specific rules on how the different urgency values are applied to the default time windows have to be defined.

The other interface to be established is for information transport from the IPS²-ES back to the IPS²-

CS. Here, data about the new delivery plan for a specific IPS² is transferred. The delivery plan contains delivery processes including their actor and the time at which they are scheduled. Also, the resources involved in the delivery process execution are specified. With this information, the IPS²-CS can then start the control on the Process level for each individual delivery process.

5. Conclusion and Outlook

In this paper, an IPS² Control Architecture is proposed to set the several levels of IPS² during the operation phase into a general context. Lifecycle level, Operation level, Process level and Effect level mutually influence each other by controlling delivery processes or a whole IPS². Each level is used to guarantee the contracted customer value on a different level and with a different scope. While the Lifecycle level focuses on the general IPS² and the design of product and service shares as well as the necessary delivery processes, the operation level uses the IPS² target values inherited from the Lifecycle level to provide a structured plan for the execution of the delivery processes. On the Process level, each delivery process is guided to provide the intended effect. Human activities and automated routines are supervised on the Effect level.

To provide the aforementioned complex control, control systems are in effect on each distinct level. Based on information about state of a machine tool or a delivery process, required measures can be derived. Setting these measures into effect has an influence on the IPS² and therefore the customer value.

With an example, a detailed view on the operation level is given. IPS²-CS and IPS²-ES are introduced as the controller and the actuator respectively on this level. The exchange of data between these systems to provide the control needed is described in detail.

Further research has to be carried out to substantiate all levels of the IPS² Control Architecture. Moreover, the interaction between the individual control systems has to be analyzed in-depth. For the operation level, the proposed interfaces have to be realized and the definition of the urgency domain is required.

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