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Determination of the Optimal Degree of Autonomy in a Cyber-Physical Production System

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Abstract

Classical productions systems are migrating step-by-step into cyber-physical production systems. The addition of much more computing power and object-bound data storage will lead to new possibilities for the advancement of autonomy in production systems. Autonomous message exchange and coordination can help to prevent quality problems (for instance wrong pairing of tool and work piece) and improve the disturbance management (for instance by faster information about current and probable disturbances).Due to the fact that nearly all improvements of existing production systems with cyber-physical systems take place in real and active manufacturing sites, on-site experiments to find out the right degree of autonomy for production objects are not suitable. Therefore a lab approach is necessary. In this contribution a hybrid lab approach to simulate various degrees of autonomy is presented [1]. The paper starts with a definition of autonomy and suggests measurement methods [2]. After a short introduction into the lab concept the results of some test runs are presented where autonomous objects perform the same production program as dumb production objects. Finally, an outlook for further research is given.

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Keywords:
Autonomy; Cyber-Physical Systems; Hybrid Lab Approach

1. Autonomy and ways to measure it

There are different ways to describe and measure autonomy. Basically, autonomy is defined as the ability of an entity to structure its own action and environment independently and without unwanted influence from the outside. Measuring protocols nowadays only exist in medicine and psychology. Therefore new definitions of autonomy are useful that can be applied on production systems. In this contribution two approaches to define the autonomy of a production system are presented, a descriptive approach and an approach which is based on the simulation of behaviour of entities on a market.

1.1. Descriptive Approach

Various fields of live and science e. g. politics, automobile industry and psychology use the term autonomy to describe the independence of field specific objects and instances. It is necessary that those autonomous actors have certain capabilities as well as liberties and rights to create and sustain a successfully performing system. While the capabilities are hold by the autonomous actors decentrally, liberties and rights are determined centrally. Autonomy in production systems gained in importance during the last years. One core capability for Industrie 4.0 (a term mainly used in Germany) or Smart Production [3] are autonomous production objects like (semi-finished)products, machines, tools or transportation means that are able to proceed information, make and execute decisions on their own [4]. To analyze autonomous production systems the authors of this contribution developed a methods that enables a measurement of autonomy of production systems and thereby gives a basis for the evaluation and comparison of various systems or their set ups [5,6]. The core element of this method is the Autonomy Index AI that puts into relation autonomous part of the considered value stream to the entire one. Other parts of the methods are an Extended Value Stream Method, that allows the consideration of relevant autonomous information in the modelling of production processes and a Data Dictionary for the documentation of further relevant process and product information of the autonomous production system. The calculation of AI is part of the following subsection.

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1.2. The Autonomy Index

The Autonomy Index specifies the degree of autonomy used in the production process. The term was chosen following the term Lean Index used in Toyotas Value Stream Design [7]. While defining the index the basis for the comparison had to be determined. There are various possibilities, e. g.:

- Number of autonomous processes : number of all processes
- Number of autonomous process steps : number of all process steps
- Autonomous controlled process time : total cycle time
- Autonomous quantity of data : total quantity of data

The practical execution has shown that the number of autonomous process steps is the most suitable of the named possibilities. Relevant data can be accorded in laboratory and even on site in the shop floor without an extensive time- and cost-consuming experimental procedures. Autonomy in production systems cant just be achieved by hardware autonomy but also by autonomy of human and software [2]. These three enablers also called levels of autonomy can be considered by means of Autonomy Index. Besides two additional key figures were defined to characterize the autonomous system more detailed: the Interaction Index II_x and the Communication Index CI_{xy}. In the following the three indices are described formally and mathematical. Their mathematical relationship is elaborated. The Interaction Index II_x describes the proportion of autonomous process steps $PS_{aut,x}$ executed with the help of communication of actors within the same level x to the total amount of process steps $PS_{all,x}$ in level x (1).

$$II_x = \frac{\sum_{i=1}^{n} PS_{Aut,x,x,i}}{\sum_{i=1}^{n} PS_{Aut,x,x,i} + \sum_{j=1}^{m} PS_{Aut!,x,x,j}} = \frac{\sum_{i=1}^{n} PS_{Aut,x,x,i}}{\sum_{k=1}^{n} PS_{llt,x,x,k}} \quad (1)$$

The Communication Index CI_{xy} (2) describes the proportion of autonomous process steps $PS_{aut,x,y}$ executed with the help of communication of actors of level x to actors of level y to the total amount of process steps $PS_{all,x,y}$ that are executed with the help of communication of actors in level x to actors in level y. CI_x describes the proportion of autonomous process steps $PS_{aut,x}$ executed with the help of communication of actors of level x to actors of all other levels to the total amount of process steps $PS_{all,x}$ that are executed with the help of communication of actors in level x to actors in all other levels (2).

$$CI_{xy} = \frac{\sum_{i=1}^{n} PS_{Aut,x,y,i}}{\sum_{i=1}^{n} PS_{Aut,x,y,i} + \sum_{j=1}^{m} PS_{Aut!,x,y,j}} \quad (2)$$

The Autonomy Index AI (3) describes the proportion of autonomous process steps to the total amount of process steps.

1.3. Autonomy as the Result of Acting on Markets

The market approach presented here [8] relies on the following abstract understanding of a CPSs degree of autonomy (DoA): The CPS acts autonomously if it decides completely self-determined (DoA = 100, autonomy). If its decisions are solely determined by others, its autonomy is zero (DoA=0, heteronomy). The CPSs are interpreted as participants of a cyber-physical market on which each individual CPS interplays with its environment. The similarity to real market mechanisms can be used to find the optimal setting for each production component and optimization dimension.

1.3.1. Assumptions

The model is built up on the following assumptions: Assumption 1: Any CPS communicates with any CPS such that a fully meshed communication structure exists. Each CPS as a market player is able to overview the market. No market anomalies with regard to information deficits distort the ideal market model. Assumption 2: The determination of the CPS specific optimum is based on the interplay of the individual CPS and its environment, which can be seen as market equilibrium.

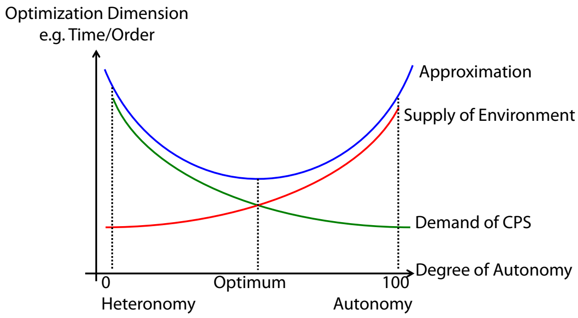

Fig. 1. Supply and Demand of each CPS

In Fig. 1 this equilibrium can be seen at the intersection of the red and green curve. Those curves are described in the following. The green curve shows the demand of a single CPS. For example, this could be a work piece that is in the search for a coloring machine. It intends to minimize its general time per order. The more self-directed it can select the required offer combination to be colored given by its environment, the smaller will be its time per order. The more other-directed those offers are selected by the environment, the greater will be the CPSs time per order. This is because further CPSs have to be considered as well and they may be preferred. Of course, the curves of the individual CPSs can be consolidated as well. Imagine, we have several CPSs as consumers of production services, so their individual demand curves can be added to a cyber-physical market demand curve. Equally, the cyber-physical market supply curve can be created based on the supplies of further CPSs (see red curve in Fig.1).The equilibrium can be found at the intersection of the red and green curve. It is referred to a pareto op-

$$AI = \frac{PS_{Aut}}{PS_{Aut} + PS_{Aut!}} = \frac{\sum_{z \in Z} \sum_{i=1}^{n} PS_{Aut,x,z,i} + \sum_{z \in Z} \sum_{j=1}^{m} PS_{Aut,z,z,j}}{\left(\sum_{z \in Z} \sum_{i=1}^{n} PS_{Aut,x,z,i} + \sum_{z \in Z} \sum_{j=1}^{m} PS_{Aut,z,z,j}\right) + \left(\sum_{z \in Z} \sum_{k=1}^{o} PS_{Aut!,x,z,k} + \sum_{z \in Z} \sum_{l=1}^{p} PS_{Aut!,z,z,l}\right)} \quad (3)$$