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Determinants of an appropriate 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 for determining an appropriate degree of autonomy for production objects are not feasible. 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 diverse 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, Production Process Characteristics

1. Autonomy and ways to measure it

There are different ways to describe and measure autonomy in cyber-physical production systems (CPPS). 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 only exist in medicine and psychology nowadays. In Artificial Intelligence autonomous agents are not dependent from the goals of other entities [3]. Agent autonomy means that agents have control over both their internal state and over their behavior [4].

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 entity behavior in a market model. Autonomy is adjustable, following van der Vecht [4], when the agent is able to choose a distinctive style of decision-making and of coping in an agent organization. There are several ways to achieve coordination within an agent organization. Approaches range from emergent coordination, where the actors are autonomous and the coordination is implicitly implemented, to explicit coordination, such as a hierarchical organization where the actors have no decision autonomy, but solely follow the orders from their superiors.

In the context of logistics processes, the following definition of autonomy was given [5]: Autonomous control describes processes of decentralized decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. The objective of Autonomous control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity. During the last years, the importance of autonomy in production systems increased fundamentally. One core capability for Industry 4.0 (a term mainly used in

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Germany) or Smart Production [6] are autonomous production objects like (semi-finished) products, machines, tools or transportation which are able to proceed information and make and execute decisions on their own [7].

This paper names two approaches to determine the right degree of autonomy, following the characteristics of a given production process. The research on agents cannot be transferred fully to production systems due to the fact that production systems consist of by design designated elements (agents) with (1) no degree of autonomy, with (2) some extent of autonomy and (3) with a high degree of autonomy. Therefore, there cannot be a unified determination of the optimal degree of autonomy but a specific determination of the degree with different results for diverse production systems instantiations.

Table 1: Classification of manufacturing systems [8]

Attribute	Attribute values			
Product range	Specification by customer	Serial products with customer-specific variations	Standard products with variations	Standard products without variations
Product structure	One-piece-product	Multiple-piece-products with simple structure	Multiple-piece-products with complex structure	
Order trigger	Manufacturing on demand with single orders	Manufacturing on demand with blanket orders	Manufacturing on stock	
Disposition	Following the customer's order	Mainly following the customer's order	Mainly MRP-based	MRP-based
Demand planning	No relevant external supply	Relevant external supply	Huge external supply	
Manu-facturing process	Unique manufacturing	Unique and small lot manufacturing	Serial manu-facturing	Mass manu-facturing
Manu-facturing organization	Construction site	Shop floor	Group-/ line assembly	Line production
Share of self-manufactured parts	Low	Medium	High	

To be able to differentiate between production systems, a classification system stemming from Schomburg [8] is used (Tab 1). The model to determine the right degree of autonomy is depicted in Fig. 1. Based on similar concepts to adjust the degree of adaptability in turbulent environments [9,10,11], there might be a discrepancy between the necessary amount of autonomy in a certain environment and the actual degree of autonomy.

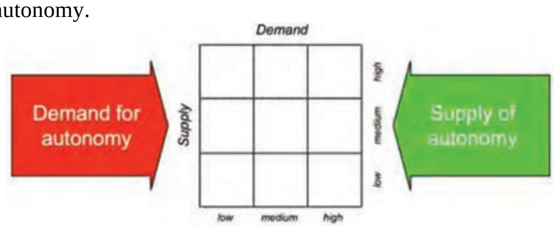

Fig. 1. Model to compare demand and supply of autonomy.

The optimal degree of autonomy can be calculated by comparison of the least necessary degree of autonomy with the actual deliverable degree of autonomy. The actual deliverable degree of autonomy can be calculated using one of the approaches briefly described below, the descriptive approach and the market-based approach. After a short explanation of the two approaches, the necessary degree of autonomy is derived from manufacturing characteristics in Tab. 1.

1.1. Descriptive approach

The core element of the descriptive approach is the Autonomy Index (AI) that puts into relation the autonomous parts of a considered value stream to the entire value stream. The calculation of AI [12] is briefly described in the following subsection.

The Autonomy Index [2] specifies the degree of autonomy used in the production process. The term was chosen following the term Lean Index used in Toyota‘s Value Stream Design [13]. 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 above-mentioned possibilities. Relevant data can be accorded in a laboratory and even on site in the shop floor without extensive time- and cost-consuming experimental procedures. Autonomy in production systems cannot solely be achieved by hardware autonomy but also by autonomy of humans and software [13]. These three enablers – also called levels – of autonomy can be considered by means of the Autonomy Index. Furthermore, two additional key figures were defined to characterize the autonomous system more detailed: the Interaction Index II and the Communication Index CI. The Interaction Index II describes the proportion of autonomous process steps executed with the aid of communication of actors within the same level to the total amount of process steps in this level.

The Communication Index CI roughly describes the proportion of autonomous process steps executed with the aid of communication of actors of the same level to actors of another level to the total amount of process steps that are executed in this level with the aid of communication to actors in another level.

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

1.2. Autonomy as the result of acting on markets

The market approach [14] relies on the following abstract understanding of a CPS’s degree of autonomy (DoA): The CPS acts autonomously if it decides completely self-determined (DoA = 100, autonomy). If the decisions of a CPS