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Dynamics of autonomously acting products and work systems in production and assembly

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ABSTRACT

Autonomous production is characterized by local and autonomous decision making of intelligent logistic objects such as work systems that adjust production rates and parts that decide which products they "want" to become and which orders they will fill. It is important to understand and have confidence in dynamic interactions of these objects and their resulting performance. In this paper the dynamic interaction of autonomous products and work systems is investigated using a hybrid simulation model and a control-theoretic model. Results obtained using both models show that these dynamic interactions can be well behaved and predictable. Through linearized models of continuous input flows at nominal rates, tools of control theory are shown to build confidence in complex system dynamic behavior of interacting autonomous logistics objects when decision-making logic is modeled in a way that makes control-theoretic analyses tractable.

1. Introduction

It is becoming increasingly difficult to ignore the fact that the complexity and the dynamics of modern production facilities and their connecting supply chains have a major impact on the performance of manufacturing enterprises. It has been shown that dynamic complexity drivers significantly affect the performance of manufacturing plants [1] and that supply chain complexity, including technology and information processing, significantly affects delivery performance [1,2]. Questions have been raised regarding the ability of present production planning and control methods to handle this challenge with their centralized control approach [3–5].

In recent years, researchers have proposed a paradigm shift from centralized to de-centralized control approaches as a way to cope with this complexity [3]. Concepts of de-centralized control, called autonomous control and characterized by decentralized decision-making in heterarchical systems [4], aspire to provide logistic objects with decision capabilities. The most significant difference between heterarchical and hierarchical systems is that objects can operate independently from each other and have equal rights to access resources [6]. With the highest level of autonomous control, master–slave relationships are eliminated, global information sharing is avoided, and intelligent objects make decisions based on local information and a minimal amount of information obtained from other objects [7].

The underlying hypothesis is as follows: by enabling logistic objects to make decisions on their own, the level of autonomous control rises and the overall achievement of logistic objectives can be increased [4]. These objectives can include short delivery times, high due date reliability, low capital tie-up costs, and desired capacity utilization [8]. Fig. 1 illustrates the hypothesized relationship between degree of autonomous control within a production system and achievement of logistic targets. It is assumed that autonomous control can use the production system's inherent and so far unused flexibility potentials to find better trade-offs between conflicting targets of production logistics, as compared to traditional, hierarchical planning schemes, in particular under variable environmental conditions. Today's production systems operate on a relatively low level of autonomous control. By increasing the level of autonomous control, the remaining logistic potential can be developed and a higher logistic target achievement can be attained. The behavior of these heterarchical systems however, depends strongly on the local decision making logic that is implemented [9]. Unfortunately, without global information, de-centralized decision-making can converge to local rather than global optima. Therefore, it is important to understand the dynamic behavior of autonomous production in order to avoid possible undesired characteristics, such as deadlock situations or the mutual amplification of system

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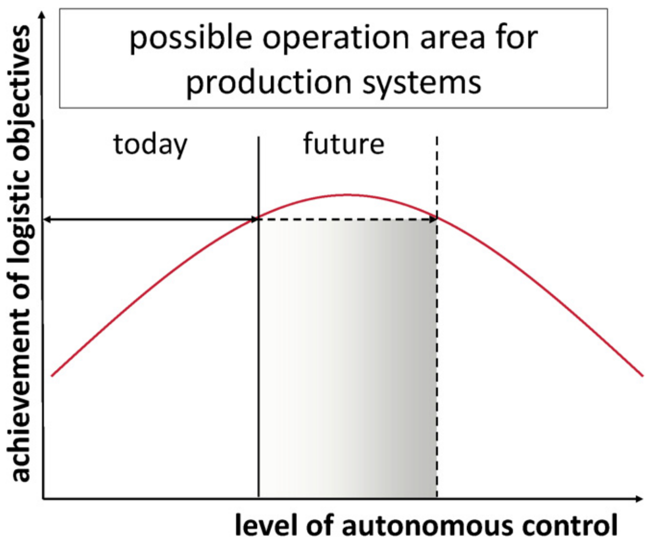

Fig. 1. Hypothesized domain of operation for production systems (adapted from [10]), in which autonomous control methods can create better compromises between logistic objectives, by exploiting inherent system flexibility.

adjustments leading to unfavorable system states that diminish performance and to gain confidence in adoption and implementation of the concept.

Various concepts have been investigated for autonomous control in production including decision-making based on Internet routing protocols [11] and biological examples such as ants [12] and bees [13]. Levels of autonomy in production logistics have been characterized, including requirements for decision alternatives within production processes [14]. Control-theoretic concepts have been developed for local regulation of work-in-process (WIP) [15] and lead-time [16] by autonomous work systems.

The purpose of this work was to study and characterize the dynamic interaction of autonomous products and autonomous work systems. This is of interest because different kinds of logistic objects can pursue individual and possibly conflicting objectives. Products, for example, can try to navigate through production in the fastest possible way by choosing work systems with short waiting queues [13], while work systems can try to maintain ideal WIP [15] because WIP determines capital employed and influences both capacity utilization and throughput times [8]. During production, autonomous products and work systems make a multitude of decisions; hence, as individual logistic objects pursue object-specific goals, their resulting interacting dynamic behavior is of essential importance.

First, the concept of autonomous product manufacturing using autonomous work systems is introduced. Simulation results are then used to illustrate dynamic behavior and show proof of concept. After that, a control-theoretic model is presented that permits quantitative characterization of the interacting dynamic behaviors of the logistic objects. Fundamental dynamic properties are derived that are difficult to obtain from simulations and verify the reliability of the interactions and the desirability of the resulting performance. Finally, the results of the simulation studies and control theoretic analyses are compared, and conclusions are drawn regarding the efficacy of pairing autonomous products with autonomous work systems in production, as well as the utility of control-theoretic analysis in this domain.

2. Autonomous manufacturing

Regardless of the decision-making logic used, the number of possible decision alternatives is crucial for the success of autonomously controlled processes. The more decisions with various decision alternatives that exist within a logistic system, the higher the logistic potential that can be realized with autonomous control methods [14]. In the following subsections, the concepts of autonomous products and autonomous work systems are defined and the nature of their decision alternatives and interactions is discussed along with flexibility potentials and decision spaces for both products and work systems in production environments.

2.1. Autonomous products

Traditionally there is a fixed linkage between orders and parts in the series manufacturing of products with many variants; i.e., the production plan of parts is predetermined and allows for little or no flexibility during the production process. Hence, in the case of customer order changes or production failures, little room for logistic maneuvers exists. By loosening the linkage between customer orders and parts produced, inherent but so far unused flexibility potentials can be developed [4]. Fig. 2 shows the decision space for an autonomous product, extended by the selection of product variants and customer orders. The autonomous product can decide the next production operation and choose, from among the available production resources, the one that should perform the operation. In making this decision, it should also take into account the different final product variants it can become and their respective current demand situation; i.e., the customer orders for this product variant.

In order to select a decision alternative from the available decision space, a general decision function can be formulated. The decision making function (f_{dm}) needs to yield the selected production operation *ps* and the selected work system *ws* to perform the operation. Furthermore because the linkage between customer order and product is loose, the decision function needs to return the set of still possible product variants *pv* as well as the set of customer orders *co* that still can be satisfied:

$$[ps, ws, pv, co] = f_{DM}(c_1, c_2, \ldots, c_n) \quad (1)$$

The selection of the decision alternative is based on the applied evaluation criteria (c_i, $i = 1, 2, \ldots, n$). The autonomous product therefore not only decides about the actual process step and the work system on the shop floor, but also about the product variant

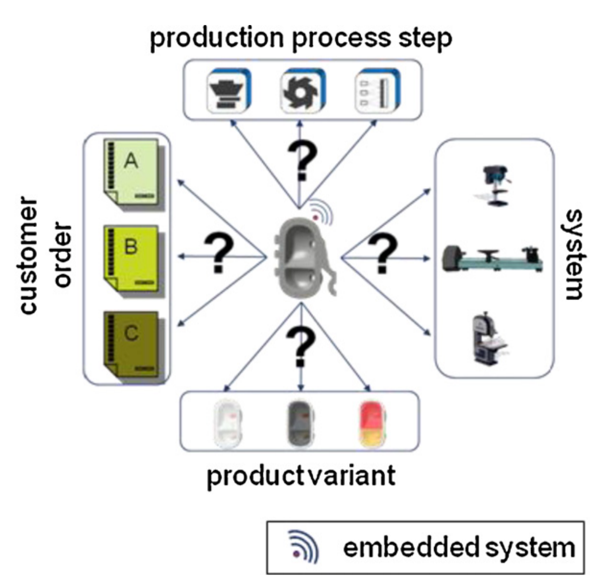

Fig. 2. Decision space of an autonomous product.