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Dynamic production control for flexibility in Cyber-Physical Production Systems using an autonomous transport system

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Abstract

The increasing demand of flexibility in manufacturing systems requires changes concerning the structure of decision processes on resource and on control level. Autonomous transport systems are able to cope with these challenges due to their capability to make decisions in an independent manner. However, the difficulty to integrate adaptive production resources in a conventional central organised production control arises. This paper presents an approach to restructure the decision process in production control based on the results of a simulation study. The method identifies a threshold between centralised and decentralised decision making with the objective of reaching a dynamic production flow.

Keywords: flexible manufacturing system (FMS); production control; autonomous transport system

1. Introduction

Manufacturing systems have to deal with the customer demand of personalised products and shorter product life cycles. These various challenges cause for production processes small lot sizes and a high amount of variants. [1,2] Consequently, flexibility and dynamics are keywords in this context. Flexibility, the ability of a manufacturing system to react to changes of the production environment [3], is precondition for dynamics [4]. Dynamics in a production environment mean that the manufacturing system can respond to and control incidents occurring in a spontaneous way [4]. Hence, this means only a flexible system can act in a dynamic way.

The concept of Industry 4.0 comprises among others digitisation and decentralisation in value adding and non-value adding processes. Using cyber-physical production systems (CPPS) that are able to analyse data themselves presents various possibilities [5]. The implementation of the central idea of Industry 4.0 in manufacturing systems affects particularly logistics [6]. Manufacturing logistics have important consequences on the throughput time. 85 % of this key performance indicator is composed of transport and wait time [7], two factors that are influenced by the organisation of logistic processes. Companies recognised the importance of meeting customer requests on schedule and its connection with logistics. Furthermore, the awareness for the need of integrating new technology concepts in logistics and the link with existing production planning and control systems rises [8,9].

Autonomous transport systems, i.e. a group of self-directed vehicles executing transport jobs, are able to meet the demand of flexibility in logistics [10,11]. The autonomous transport vehicles have certain degrees of freedom concerning decisions like navigation, obstacle avoidance or communication and can process data in an independent manner [12]. Nevertheless, the transport system cannot operate in a completely independent way, as it is still part of the processes in the manufacturing system. Therefore, one important question is how to integrate

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these adaptive production resources in the generally central organised production control system. The interaction between centralised and decentralised decision processes has to be structured regarding which entity takes which decision.

As a result more and more dynamic effects occurring in production influence the organisation of planning and control processes [13,14]. Production logistics play an important role in manufacturing systems [6] and therefore, there is a need of flexibility that autonomous transport systems can meet due to their intelligence as well as their independence regarding certain decisions.

This paper introduces an approach to categorise decisions that autonomous intelligent systems take on a decentralised level and those that are allocated to superior control systems in order to guarantee a dynamic production flow.

2. State of the art

Before presenting a method classifying situations suitable for decentral and central decision processes, relevant literature is summed up. The current state of the art concerning resources for logistic operations in CPPS, autonomous transport systems themselves and production control in general is considered. In this context, gaps can be recognised regarding the integration of an autonomous transport system in production control. One central question is how to split decisions between the autonomous vehicles – decentral entities capable of taking their own decisions – and central production control.

2.1. Cyber-physical production systems

Lee [15] defines cyber-physical systems (CPS) as "integration of computation and physical processes". This underlines the importance of creating smart production systems, i. e. connecting CPS-components using common means of communication.

Smart factories based on CPS are called CPPS. This includes that the conventional automation pyramid dissolves more and more to the benefit of intelligent self-organising resources. Challenges regarding resources are the organisation of the different participants and their individual skills. [16]

Intralogistics play an important role in manufacturing systems in general (see chapter 1) and hence, they are also a central player in CPPS. There have to be transport technologies capable to interact with the intelligent manufacturing system, i. e. other machines on the shop floor, the production employees and superior planning and control entities. [17]

2.2. Autonomous transport systems

As introduced in chapter 1, autonomous vehicles can present a medium to meet the need of flexibility in manufacturing processes. They are organised in a network, called autonomous transport system. Every vehicle disposes of a safety system for the interaction with its environment. In addition, independent vehicles have the necessary sensors for their individual skills. [18–20] These skills result in abilities that enable the resources to be some kind of intelligent and to interact with the other autonomous vehicles constituting the autonomous transport system.

The challenge for the integration of autonomous resources in production systems is to benefit on the one hand of the resources' capabilities and guarantee at the same time to reach the target of production logistics like reliability and availability. There are several projects presenting approaches for an autonomous control of logistic systems [21,22]. In these methods, the transport systems are treated in an isolated way without considering in detail superior control levels of manufacturing systems.

Regarding autonomous vehicles organised in a network, there is a lack concerning the classification of their degree of autonomy based on their capabilities to act in an autonomous manner.

2.3. Production control

The production planning and control embraces the two tasks of planning and controlling manufacturing processes. In this paper only the short-term oriented part, production control, is considered. This process starts with the task allocation where the verification of the availability of the needed resources takes place. Afterwards, the production tasks are executed by the specific resource. During the production process, production is supervised, i.e. the second part of production control. By monitoring all production parameters, there is a high amount of data exchange between the production resources and the control entity. [23]

Because of the increasing realisation of CPPS and the ability of adaptive resources to analyse data in an autonomous way, see section 2.1, the current approaches of production control have to be expanded in order to be able to handle this high potential of data analysis and connectivity. One approach for a higher degree of connectivity and communication is represented by a service-oriented architecture (SOA).

This concept is based on information exchange between the involved production resources, which are figured as modules. At this platform, these modules are offering their services and so a suitable task allocation can take place. [24]

Another concept for more flexibility in production control is the implementation of swarm intelligence for intralogistics. The mobile resources are able to connect and have the ability to learn from each other. So an external party for organising them and planning gets redundant. This flat hierarchy promotes a higher dynamic. [25]

Apart from these general concepts, there are also some special approaches where central and decentral components of production control are combined.

Hortskemper and Hellingrath [26] propose the implementation of "order allocation flexibility". This means that it is possible to assign the physical products to specific customer orders even at a late point of production. The algorithm works centrally organised, but the ability of decentral communication of the CPS is a requirement.

Using the concept of Prehofer and Zoitl [27] decentral decision making is exercised. Nevertheless, limitations for the power of the CPS are given because they can only decide within a centrally determined frame of decision alternatives.

Kousi, Michalos et al. [28] implemented a SOA to organise material supply operations in a dynamic way. In contrast to the approach proposed in this paper, the general assignment of decision power to different fields of application, Kousi, Michalos et al. [28] focus specific logistic processes.

It can be seen that there are many proposals for generating flexibility in production. However, a proved concept for combining conventional production control organisation with arising possibilities of autonomous decision making is missing. The approach in the following chapter introduces a possibility to define a threshold for the application of central decision situations in combination with decentral ones.

3. Concept

Regarding the aim of this method, a guideline to differ between specific situations in which a central or a decentral decision making process should be preferred is presented. This depends on the kind of manufacturing process that is considered. With this classification, it is possible to create a more dynamic production flow. Figure 1 presents an overview of the concept and the different options of communication in a manufacturing system using an autonomous transport system.

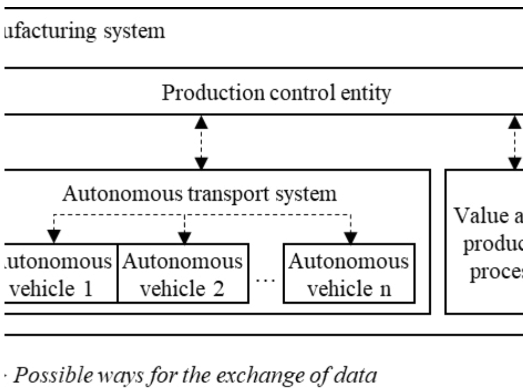

Fig. 1. Concept of the proposed method.

The centralised decision making process is defined as follows: The choice occurring during the production process is given to a central production control entity that is able to access every available information about the manufacturing environment. In contrast to this, decentral decision making means that the autonomous transport system does not communicate with the central production control entity when they are forced to make decisions in order to fulfil their task. This means that the vehicles have only access to a smaller information basis existing of their own previous experiences and autonomous data analysis.

As advantage of a central approach, the possibility of a global optimisation of production flows has to be considered because of the wide information basis. For a decentral approach the positive aspect is the higher flexibility and scalability because of the local closeness to the problem. [24,29]

In addition, in the context of central control systems the disadvantage of higher processing time of data analysis occurs because of the large amount of data. [1]

For answering this problem, the approach comprises three decision situations that are part of the two steps of production control, task allocation and production supervision. Additionally to this sub-division the situations differ concerning their time dependence of the situations' occurrence.

3.1. Task allocation

This first step of production control also represents the first decision by starting the simulation scenario, called resource allocation. When half-finished products are reaching the production excerpt, the problem of allocating the attended tasks to the autonomous transport resources occurs.

On the one hand this allocating procedure can be fulfilled by a decentral communication process between the involved CPS. Because of the decentral communication, the main priority for delegating the task to an autonomous transport system is its local closeness to the purchaser.

On the other hand, a central organised allocation could be exercised. The decision maker commands the information about the product specific suitability of all transport systems. So the most suitable resource can be chosen to fulfill the task.

3.2. Production supervision

For this production control task two decision processes are elected within this approach. These situations differ in the time dependence of their appearance. The decision situation handling long-term disturbances is called navigation, the one handling short-term disturbances is called obstacle avoidance.

The autonomous transport systems are confronted with the situation *navigation* during their path planning whenever they have more than one possibility to reach their destination. For the central case, they know if some possible ways are not drivable and how long a possible blocking lasts. Because of its wide information basis, the central decision entity also knows how much time alternative ways would take and can therefore choose the alternative with the lowest costs. By deciding themselves, the resources do not have the information about the duration of the blocking. So they always decide for a bypass, although waiting for the concerned way getting drivable again, could be connected with less time loss.

For sudden occurring obstacles during the locomotion of the resources, the decision situation *obstacle avoidance* is developed. In this case, a central decision maker would check if it was possible to drive around the obstacle or if other transport systems were near and therefore, create the risk of a collision. Within decentral decision processes, it is only possible to identify the risk of collision with the help of the sensors of the resources. The challenge in this case is the range of this sensors and subsequently the data acquisition.

By combining all possible combinations of this scenarios and evaluating them, a threshold between the central and decentral organisation leading to high dynamic in production flow may be identified.

4. Simulation study and evaluation

For the implementation of this approach, a discrete event simulation study with the use of Siemens Tecnomatix Plant Simulation is developed. For comparing and analysing the simulation results, the processing time is used because of its significant meaning in production control [23].

4.1. Model

The environment of the simulation consists of an excerpt of a production process. Three different half-finished products entering the excerpt are generating a task for the service-oriented transportation modules.

There are four types of transport resources, based on the products of the Grenzebach Maschinenbau GmbH, that are able to move the three different types of products. The suitability of each transportation resource for each product is modelled by differing velocity.

When the products are finished after the different production steps the performing machine, represented by a CPS, communicates a transportation order. The scenario ends with the autonomous transport systems transporting the products to their specific outgoings. Figure 2 shows the production process chosen for the model.

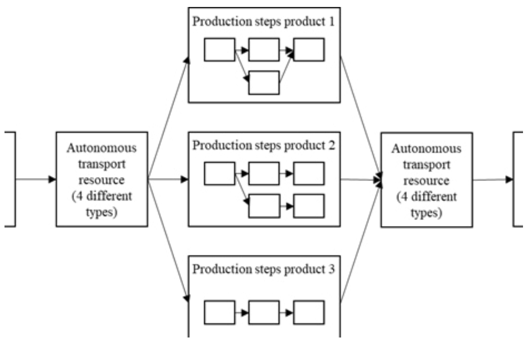

Fig. 2. Representation of the production process for the simulation study.

The processing time for the evaluation is composed of the overall time that is needed to produce a specific amount of products in this scenario.

4.2. Simulation

By running the simulation based on the model presented in section 4.1, the three different decision situations, explained in section 3, occur various times. The performance in these situations, either of the central or of the decentral decision unit, affect the processing time of the current simulation experiment. As a result, there are eight possible combinations out of the three decision situations for evaluating a threshold between central and decentral decision making which have to be compared (see table 1 left column).

Each of these eight scenarios is executed several times with variating random numbers leading to different environmental conditions in the production scenario. In the right column of table 1, there are the corresponding processing times represented by the mean value combined with standard deviation over the executed simulation runs.

Table 1. Results of the simulation study.

Scenario *[resource allocation – navigation – obstacle avoidance]*	Processing time *[h]*
central-central-decentral	4,917
decentral-central-decentral	4,921
central-decentral-decentral	4,935
central-central-central	4,975
decentral-central-central	5,071
central-decentral-central	5,090
decentral-decentral-central	5,191
decentral-decentral-decentral	5,224

The results can be seen as significant and allow an interpretation as the difference between the processing times of about 0,3 h is meaningful in the chosen production scenario.

4.3. Evaluation and interpretation

Due to the optimisation criterion of the lowest processing time, table 1 yields in the pictured order. Consequently, the scenario with central resource allocation, central navigation and decentral obstacle avoidance seems to be the best decision assignment. The two centrally organised decision situations are long term oriented. All information that is needed for the decision is already available and plannable. Therefore, it may be assumed that such decision structure should be organised with the help of a central entity. In contrast to this, the *obstacle avoidance* is implemented as a short term oriented and sudden arising challenge where the data basis has to be created at this specific point of time. Because of that, it can be derived that unplannable data analysis is better done by the autonomous resources themselves.

These interpretation approaches can be verified by further examining table 1. The three scenarios with the lowest processing time are organised on decentral level for the *obstacle avoidance*. Here the advantage of decentral autonomous data analysis can be seen in situations occurring short-term in order to create higher dynamics.

The advantage of a wide information background in case of central decision stands out in the fact that the scenario with all situations organised in a decentral way delivers the poorest performance. Hence, the advantage of decentral data management does not count for long-term oriented decisions.

5. Conclusion

When analysing the current state of the art regarding autonomous transport systems and their integration in manufacturing systems, among others a lack is seen in how to deal with decisions in production control and the characteristics of autonomy in the context of transport systems. This paper proposes an approach in order to restructure the decision process in production control on decentral and central level for manufacturing systems with an autonomous transport system.

The simulation study showed that decisions taken in the context of the control of intralogistics can be categorised regarding the required data base and the affected time frame (see chapter 4.3). There is no additional value in relocating decisions from decentral to a central control level that concern only one resource and that need to be taken in near real-time. In contrast, an optimised overall processing time appears if a central control entity takes decisions affecting a resource and its environment as well as more remote future. This means decision situations have to be classified regarding the available and essential data that is collected by the different production means and that can be transformed into knowledge. The result of creating knowledge based on data provided by several intelligent resources and merged on a central control level allows other conclusions than those done by a single autonomous resource. The simulation demonstrated this with the help of the three shown scenarios *resource allocation*, *navigation* and *obstacle avoidance*. In addition, the manufacturing system needs to be categorised concerning time, i. e. a classification of short- and long-term depending on the processing times of value-adding steps and the overall through-put time in the production process.

That is why it can be stated that the temporal impact and the necessary information base for decision making are the relevant criteria for a threshold between decentral and central decisions. The chosen scenario showed this, however the proposition needs to be further specified by additional studies. This comprises research on the correlation between the type of manufacturing system, the used production control structure and related ways of decision making as well as taking into account the properties of the autonomous transport system.

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