DOI: 10.2195/lj_NotRev_gaertner_en_202206_01
URN: urn:nbn:de:0009-14- 55282

Decentralized Manufacturing Control Implementation in a Cyber-Physical Test Field

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How can a decentralized manufacturing control concept be implemented and bring about success? To answer this question, a cyber-physical test field is under development at the University of Applied Sciences Hamburg, Germany. This article gives insight into the test field for decentral manufacturing control which can be represented as a "swimming pool" model. This analogy focuses on the freedom of the production orders to decentrally negotiate among each other on scarce resources such as the machines and the transport capacity. The transport means are automated guided vehicles (AGV) which allow the production orders to move freely within the limits of the pool, namely the production itself. Production orders should cross the pool from order release on the left side to order completion on the right side of the pool using the AGVs. Though, production orders may negotiate independently about the scarce machining capacities. Equipped with given customer priorities, a production order may want to bargain for a swimming lane with expensive but fast CNC machining capacity, while a different order may prefer a parallel swimming lane offering an inexpensive but slow conventional machining service.

Our research in this field has shown that a well-organized communication process between all entities in the system is crucial to implementing such a decentrally organized swimming pool model. Therefore, this article focuses on describing a negotiation mechanism to support decision making between those entities. Technical enablers such as an MQTT communication broker and a suitable simulation environment are supporting the overall concept. It is to be learned to what extent all decentralized entities of the cyber-physical production system act in a resource-conserving and value-adding manner.

[Keywords: Decentralized Manufacturing Control, Production, Agent Theory, Decision Making, Automated Guided Vehicle (AGV), Cyber-Physical System (CPS), Message Queue Telemetry Transport (MQTT)]

Wie ein dezentrales Fertigungssteuerungskonzept realisiert werden und Erfolg herbeiführen kann, wirft noch immer Fragen auf. Daher wird an der Hochschule für Angewandte Wissenschaften Hamburg, Deutschland ein cyber-physikalisches Testfeld unter Verwendung von fahrerlosen Transportfahrzeugen (Automated Guided Vehicles AGV) entwickelt. Das Testfeld kann als ein "Swimmingpool"-Modell dargestellt werden. Diese Analogie beschreibt die Freiheit der Produktionsaufträge, sich mit Hilfe der AGVs dezentral innerhalb der Grenzen des "Pools", also der Produktion selbst, zu bewegen. Die Produktionsaufträge sollen den Pool von der Auftragsfreigabe auf der linken Seite bis zur Auftragsfertigstellung auf der rechten Seite des Pools durchqueren. Dabei können die Fertigungsaufträge unabhängig voneinander über die knappen Bearbeitungskapazitäten verhandeln. Ausgestattet mit bestimmten Kundenprioritäten kann ein Produktionsauftrag um eine Schwimmbahn mit teurer, aber schneller CNC-Bearbeitungskapazität verhandeln, während ein anderer Auftrag eine parallele Schwimmbahn mit preiswerter, aber langsamer konventioneller Bearbeitung bevorzugt.

Unsere Forschung auf diesem Gebiet hat gezeigt, dass ein gut organisierter Kommunikationsprozess zwischen allen Entitäten im System entscheidend für die Umsetzung eines solch dezentral organisierten Schwimmbadmodells ist. Daher konzentriert sich dieser Artikel auf die Beschreibung eines Verhandlungsmechanismus zur Unterstützung der Entscheidungsfindung zwischen diesen Entitäten. Technische Enabler wie ein MQTT-Kommunikationsbroker und eine geeignete Simulationsumgebung unterstützen das Gesamtkonzept. Es soll herausgefunden werden, inwieweit alle dezentralen Entitäten des cyber-physischen Produktionssystems (CPS) ressourcenschonend und wertschöpfend agieren.

[Schlagworte: Dezentrale Produktionssteuerung, Produktion, Agententheorie, Entscheidungsfindung, Fahrerloses Transportsystem (AGV), Cyber-Physikalische Systeme (CPS), Message Queue Telemetry Transport (MQTT)]

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1 Introduction

Agent theory has been discussed for thirty years. But the time was not ripe yet. We all were sceptical. After all, we had learned in school that global maxima determined by a central unit yield better results than decentrally determined local maxima. Then, marketplaces such as eBay taught us that auctions where we ourselves could negotiate with other market participants are quite interesting. Now, the spread of wireless internet and low-cost sensor technology is playing into our hands, even when implementing our own home control systems. Recently, we had to learn that cyber-attacks on central systems are no longer limited to large companies while attacking decentral systems can never paralyze a whole company. By now we have enough tailwind to admit that centrally managed computer systems do not support local decision-making criteria sufficiently which our foremen repetitively consider in their daily business on the shop floor. It is time to relieve our foremen from these simple decisions in an appropriate way.

2 Decentral Approach

The idea of meeting increasing requirements of a flexible and multi-variant production by using agent theory was taken up by Weigelt in 1994 when the fourth industrial revolution had hardly begun. [Wei94] After almost a quarter of a century, an agent based decentralized manufacturing control system is anything but fossilized. The price erosion for sensors, microcontrollers and wireless data transmission has progressed over the decades and is spurring the implementation of such industry 4.0 applications. [Sch13] The economic potential arising from the introduction of such systems particularly results from the enduring advantages of no longer wasting valuable resources of foremen on repetitive decisions. Instead, intelligent orders shall coordinate their decision-making by negotiating capacities of resources independently among themselves according to defined rules of the game.

Schreiber points out a need for a test field which goes beyond simulation studies and implementations of low complexity. Gehlhoff and Fay describe a use case which considers the complex interrelationship between transport and machine availability. [May09] Without a generalization of the various individual findings on the positive effects of decentralized systems, industry would not make the leap towards implementation of such structures. [GLSM21]

The approach of the University of Applied Sciences Hamburg is to build a decentrally controlled production using automated guide vehicles (AGVs). The performance of a production scenario constructed with AGVs is essentially characterized by the fact that this approach can be expanded at will and is particularly flexible in the event of changes in processes and infrastructure. [WHSW08; Gre21] It shall be started with setting up a moderate sized but expandable basis as described in [MAZG17]. Though the design of this basis must consider all the needed complexity of decentralized manufacturing control. By proceeding in this way, a clear scenario can first be implemented and validated. Such a test field is currently under development. As a next step, the system can be scaled up to a larger test field with more machines, AGVs and production orders.

3 Negotiation Mechanism

The concept of decentral manufacturing control can be represented as a “swimming pool” model. [MAZG17] This analogy focuses on the freedom of the AGVs for decision making and acting within a certain area, namely the production itself. Thus, Greb invented a production scenario with the goal of developing a software demonstrator to simulate the information flow between decentralized entities of a manufacturing control system. [GGV20] The core of decentralized manufacturing control is the communication between all entities in the system in the decision-making process. [Tro17] This simulation is intended to prove that production can be run successfully without human interference.

In Greb's scenario, orders are to be processed by machines. The material for the orders is stored in intelligent load carriers with built in microcontrollers using wireless data transmission. The microcontrollers hold the order information and intelligence. The wireless data transmission serves to communicate with the scarce resources, such as machines and AGVs. When an order is first released into production, the intelligent load carrier enquires a pickup for transport to a machine. The AGVs then start a negotiation process as to who will take over the transport order (Figure 1). [Var19]

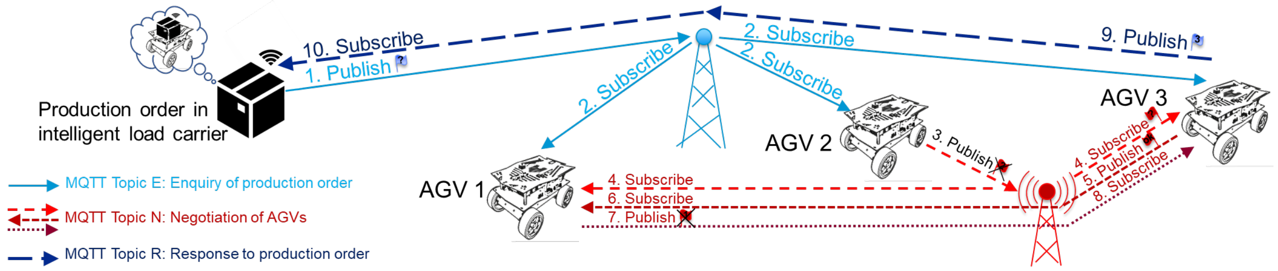

Figure 1. Intelligent load carrier initiates AGV’s to negotiate on a transport order [Gre21]

The newly released production order which is loaded into an intelligent load carrier publishes its enquiry for being transported to a first machine (see figure 1) using topic E (Enquiry). A topic describes the subject of the message, such as here the request of the load carrier to transport the production order from one machine to the next. Such a transport request is technically transmitted with the help of the MQTT broker.

The MQTT broker is the only central unit in this otherwise decentralized system. The MQTT broker ensures the exchange of messages between the entities on a technical level. For machine-to-machine (M2M) communication between the entities, the MQTT (Message Queue Telemetry Transport) protocol is used. According to the publish-subscribe mechanism of this communication protocol, an entity publishes a request on a specific channel which is received by the other subscribing entities. In practice, a channel is also referred to as a topic. [Lav09] Other protocols following the same principle, such as the significant OPC-UA protocol (Open Platform Communications Unified Architecture), are not used in this case in favour of the comparatively simple implementation and short protocol of MQTT.

Besides the production order, other entities in this scenario are three AGVs, all of which have subscribed to topic E and thus all receive the enquiry. In topic N (Negotiation), the negotiation between the AGVs takes place. At first, AGV 2 declares to take over the role of the publisher while the other AGVs listen. In this topic N, AGV 2 confirms to the other vehicles that it rejects the request because its vehicle is occupied. After that, it hands over the publisher role to AGV 1. The free AGV 1 and 3 begin to negotiate about the amount of the travel costs for the order.

After clarification in topic N, AGV 3 finally uses topic R (Response) to announce its response to the enquiry of the production order that AGV 3 will take over the transport order. Greb implemented the described negotiation process of a decentralized production control in a software demonstrator. [GGV20]

4 Simulation Environment

The software implementation requires a special programming and simulation environment to test the simultaneous, independent program execution of multiple decentralized entities. The partial developments are yet to be combined to a cyber-physical overall system. After validating the self-control of the orders in the programming environment, the next step is to harmonize the developed hardware concept with the software modules of the entities in a physical production test field.

Figure 2 sketches the basic structure of such a programming environment. Each window represents a separate terminal which executes the program code of an entity independently of the other entities and represents the microcontroller installed on an AGV or in an intelligent load carrier in the real environment. The four small windows on the top left represent the order information contained in the load carriers. The three windows on the right are the AGVs involved in this production scenario. The window at the bottom left represents the third category of objects, namely the machines in the production. [GGV20]

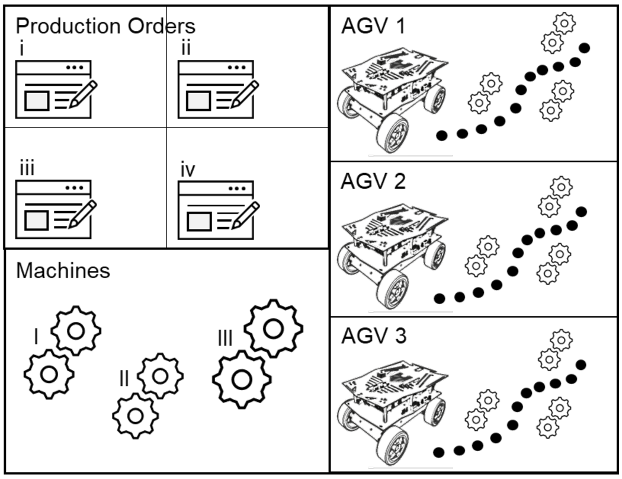

Figure 2. Developer's screen structure of programming and simulation environment for numerous independent entities.

The advantage of such a programming environment is that the developed and integrative tested program codes in this environment can be easily rolled out from this environment by uploading them to the physical entities such as the AGVs. This approach paves the way for a physical implementation.

5 Cyber-physical Test Field

The next step after validating the software with simulated decentralized entities is to roll out the software to microcontrollers of the small load carriers, AGVs, and machines. These microcontrollers must interact with the actual objects in such a way that they know their state (e.g., the current location of the AGV) and consider this information while negotiating with the other entities. Only that way, software and hardware can collaborate in a cyber-physical system.

Varal has laid one of the essential foundations by designing a test field for the decentralized control of an automated guided vehicle and implementing it step by step in the form of several Minimum Viable Products. [SS1] A Minimum Viable Product represents a still incomplete but usable version of a system or a product, where the function is limited to the essential features. Thus, Varal constructed a simplified but representative production environment and scenario. The demonstrative production scenario includes the production of a multi-variant and configurable product. Depending on the configuration, the products are manufactured on up to three machine groups containing seven machines. Communication and negotiation readiness of active entities of the system characterize the decentralized

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manufacturing control. In the scenario described, production orders are linked to the intelligent load carriers. They negotiate among themselves about the scarce resources of the processing machines and the use of the likewise limited number of AGVs which transport the orders between the stations. [SS1]

For the motion control of AGVs, a variety of methods can be used. Particularly robust navigation methods are usually based on optical or inductive guidelines in the floor, on cross bearings using a laser scanner, or on transponder technology, in which vehicles are guided via support points applied to the floor. At the production test field of the University of Applied Sciences Hamburg, the AGVs receive their sense of direction via guidelines applied to the ground and Radio Frequency Identification (RFID) tags at the intersecting guidelines. The guidelines are in high colour contrast with the shop floor and allow line-tracking sensors to orient themselves in the hall for navigation purposes. To find the shortest route from the location of the load carrier to its new destination, the A* algorithm is used. The A* algorithm has a particularly high performance with a low computational cost and is easy to implement. The basic functions of the designed AGVs and those of the small load carriers could be validated by Varal by test drives in a simplified scenario in the test field in real time. [HH17]

6 OUTLOOK

As an outlook, the partial developments in the test field of the University of Applied Sciences Hamburg shall be combined into a cyber-physical overall system. After validating the self-control of the orders in the programming environment, the next step is to harmonize the hardware concept developed by Varal with the software components of the entities in a physical production test field.

The easier it becomes to implement robust solutions for the decentralized decision-making and solution competence of the subsystems, the more interesting decentralized manufacturing control will be for industrial use. The advantages of decentralized manufacturing control can then be fully exploited, including simple modular expansion, flexible deployment, and low probability of an overall system failure. [GF20] In the far future, the self-controlling and self-optimizing approach may even be extended beyond company boundaries e. g. by including contract manufacturing, but furthermore to entire value chains. [MDP13]

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