Decentralized, Self-optimized Order-acceptance Decision of Autonomous Guided Vehicles in an IoT-based Production Facility

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***Abstract*—The paper presents an approach to the structuring and hierarchical ordering of IoT-based production facilities in the context of Industry 4.0 (I4.0) that helps to reduce the overall complexity of the system by dividing it into different subsystems with defined interfaces. The focus is on autonomous guided transport vehicles (AGVs) because they are a vital element in innovative production facilities. After detailing their structure, we will describe the exemplary application: the decentralized order-acceptance decision by AGVs that communicate with one another via IoT-based communication technologies such as WLAN and jointly decide which vehicle will accept a transportation order to achieve an optimum result in terms of energy consumption and transportation time for the entire production facility.**

***Index Terms*—IoT, I4.0, decentralized, AGV, WLAN, self-optimized**

I. Introduction

In the joint project Methods and Tools for Synergetic Conception and Evaluation of Industry 4.0 Solutions (Synus) that involves five professors of the Technical Universities of Braunschweig and Clausthal as well as Ostfalia University of Applied Sciences and is funded by the European Fund for Regional Development (EFRE), a model-based tool is being developed that helps to evaluate costs and benefits of Industry 4.0 solutions for small and medium-sized enterprises (SME) to provide support and advice for the latter when it comes to implementing the solutions. The focus on Ostfalia's subproject Model-based Conceptual Design and Evaluation of Industry 4.0 Solutions for Interconnecting Mechatronic Components in Production Systems through Digitization (MiMec) is the modelling and simulation of networked mechatronic components in already existing industrial facilities and available I4.0 solutions as well as a systematic integration of autonomous transport vehicles by means of a complete digital interlinking in intelligent, cyber-physical production facilities.

One of the greatest challenges facing production is to fix reliable schedules for the production of multi-variant or customized products in very small batch sizes or even as a single-unit production [1]. The production department must be able to react flexibly to these small batch sizes [2]. They imply long changeover- and downtimes as well as substantial staff costs and thus pose huge challenges for the enterprises having conventional or highly automated production facilities. For an autonomous production facility, AGVs are of vital importance because the transport of goods between the machines or between them and the storage can be affected only by these transport vehicles [3]. When it comes to implementing the step from a highly automated to an autonomous production, the functionalities of conventional transport vehicles are inadequate. An AGV that is to be employed in an autonomous production facility has to fulfil several requirements derived from the problem statement, especially as regards communication and interaction between the AGVs themselves and between them and the production facilities.

The present paper will describe an approach to structuring and hierarchically organizing IoT-based production facilities in the context of I4.0 that makes the complexity of this highly interlinked system manageable. The focus here is on AGVs that will be explained in detail. With the aid of an exemplary application we will detail the functioning of the decentral order-acceptance decision that is the result of the communication and interaction of several AGVs and production facilities for the purpose of an order completion that is optimal as concerns energy consumption and transportation time. This application is proof of the great significance that intelligent and highly interlinked vehicles have in the production environment.

II. Methodology and System Structuring

Mastering the complexity of the overall system and of the interdisciplinary research- and development process in the fields of mechanics, electronics as well as mechanical engineering, information- and communication technology requires systematic structuring of the entire mechatronic system.

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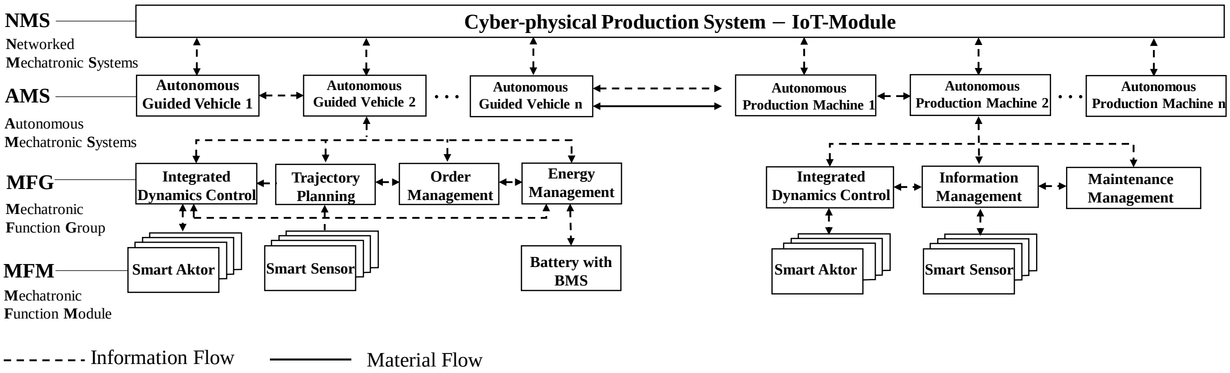

Figure 1. Structuring and hierarchization of an IoT-based I4.0 production line.

By means of the mechatronic structuring according to [4] the overall system is classified and hierarchically structured into sub- resp. partial functions in a “top-down” process starting out from the principal function, with individual functions being encapsulated in modules with defined interfaces; in view of fulfilling more complex functionalities, these modules are arranged in groups. This mechatronic structuring is done on four levels as displayed in Fig. 1:

- **M**echatronic **F**unction **M**odule (**MFM**): The MFM constitutes the lowest hierarchical level. MFMs consist of mechatronic systems that cannot be divided further, including the basic structure, sensor- and actuator systems, and information processing. Every encapsulated MFM has a defined functionality and describes the dynamics of the system.
- **M**echatronic **F**unction **G**roup (**MFG**)**:** Coupling several MFMs and adding information processing yields an MFG. Using the subordinated MFMs and their actuating systems, MFGs enable realization of more sophisticated functions such as integrated dynamics control, trajectory planning, or order management.
- **A**utonomous **M**echatronic **S**ystem (**AMS**)**:** Combining several MFGs and MFMs yields AMSs that may be, e.g., autonomous production machines or AGVs. After processing the available information yielded by the mechanical supporting structure and the sensor system the AMS sends appropriate orders to the subordinated MFGs and MFMs. The AMS also has informational interfaces to other systems.
- **N**etworked **M**echatronic **S**ystem (**NMS**)**:** When several AMSs are operated in parallel, e.g., for processing a customer order, a higher instance is required to coordinate them. This purely informational coupling on the topmost level is an NMS resp. in our case a cyber-physical production system that corresponds to an I4.0 production line or an I4.0 factory. This superordinated cyber-physical production system manages product information and transmits them to all relevant components of the production line, e.g., via WLAN.

This modular structuring and hierarchical ordering of the autonomous production facilities by means of I4.0 solutions enables any number or sort of combinations of different modules to make up complex overall systems. In order to ensure that the modules are reusable and compatible with one another, it is indispensable to select the most adequate interfaces.

Subsequent to mechatronic structuring the next step is mechatronic composition. Here, in a “bottom-up” process starting out from the lowest hierarchical level, every module is laid out and validated in a consistently model-based, verification-oriented process before successively being integrated into the more complex overall system.

III. Conception of the Autonomous Production Facility

A. State of the Art

The term Industry 4.0 was first coined at the 2011 Hanover Fair and illustrates the industry in a state of flux. Changes in industrial production were in many cases so far-reaching that they were perceived as no less than a revolution. Now production is considered to be a complex information-processing system whose core element is the use of information- and communication technology. Machines controlled by small, integrated systems – so-called embedded systems – are not only interconnected with the entire company network but even integrated into a worldwide communication network, the Internet of things (IoT). This gives rise to so-called cyber-physical systems (CPS) that describe the merging of the real and the virtual worlds [5].

A special task in the context of I4.0 falls to autonomous transport systems (ATS) that are in-company, floor-bound conveyor systems comprising automatically steered vehicles for transporting material in intra-logistics [6]. At the core of an ATS there are the AGVs. Most AGVs currently on the market (e.g., Weasel from the SSI Schäfer company and AGV-A35046 from Creform) are highly automated. Their way of operation can be described as follows:

- The AGV receives tasks from the coordinating control and maneuvers track-bound from a source (load pick-up) to a destination (load discharge).

- The coordinating control, a central computer, takes on the task of controlling and commissioning all AGVs.
- Vehicle guidance and navigation are realized by a device for position detection and location determination, for instance on the basis of track-bound road-marking systems or position marks.

B. Requirements on an Autonomous Production Facility

For tomorrow's production that requires absolute flexibility and autonomy in production machines and transport vehicles, existing transportation systems are not suitable because they are not autonomous, unable to communicate and incapable of making intelligent decisions. In view of the implications of I4.0 and with regard to the state of today's production, an autonomous production facility is especially capable of:

- Manufacturing customized products (batch size 1) because AGVs and autonomous production machine do not need the exact same production sequence;
- Continuing production in the case of interruptions (AGV breakdown, section blocked), environmental disruptions (accident, gridlock, etc.) or obstacles (worker, toppled goods, etc.) because AGVs are not track-bound and enable evasive manoeuvers or re-routing,
- Continuing production even if the central coordinating control failed because decision making and commissioning are carried out decentrally.

C. Autonomous Production Facility with I4.0

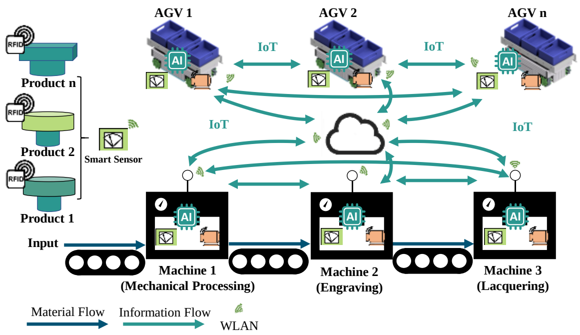

Figure 2. Individual I4.0 production line based on IoT-technology.

Fig. 2 displays the example of an autonomous production facility. The existing production machines and AGVs are complemented with smart sensors, smart actuators, and artificial intelligence so as to process different sensor signals and make decisions themselves. Taking the product as the central element of production, at first product specifications are defined for the components to be able to process the order. With regard to customized single-unit production that is one of the subtargets of I4.0, a sensor- and a product-ID were introduced. Sensor-ID is a unique combination of numbers enabling allocation to a product-ID identifying the product type. By means of information technology, e.g., RFID and IoT, all necessary information on the products to be processed can be saved and the current states of the respective machines can be exchanged among them so as to ensure self-organization of the production activities. The smart sensor reads out the RFID tag on the products and uses a communication module for transmitting production information to the corresponding production machines via WLAN. Then the production machines identify the necessary processing steps from the RFID tag and adapt soft- and hardware to the product to be processed. Thus in an autonomous production facility, information- and material flow are disconnected. This separation opens up a multitude of opportunities for optimizing production, such as shortening of processing times by means of intelligent algorithms. Moreover, there is certainly potential for improvement in other areas, e.g., consumption-based parts ordering or predictive maintenance management by remote monitoring.

IV. Autonomous Order-Acceptance Decision of Networked AGVs

A. System Description of AGV

For transmitting the driving torque to the road surface the AGV uses the mecanum wheel that enables omnidirectional driving maneuvers. Contrary to transport vehicles with conventional wheels the AGV needs no space for maneuvering and can do rotations around the vertical axis [5]. Another major advantage of an AGV having mecanum wheels is its ability to park in any direction.

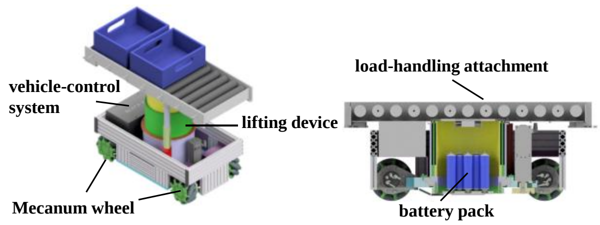

Figure 3. Concept of the AGV.

It follows from the VDI 2510 guideline that different energy-supply strategies result from different energy sources (e.g., fossil fuels or electricity). Fig. 3 shows an overview of the concept of the AGV. Because of their exhaust emissions, combustion drives for transport vehicles have become obsolete for intra-logistics, which is why energy supply to the AGV is realized by a battery pack having a nominal voltage of 48 V, taking into account the scope of application and the specific requirements (e.g., maximum load and maximum speed).

In order to meet the specification of autonomy the load-handling attachment of the AGV is laid out to play an active part. This means that according to circumstances the AGV will be able to handle the load on its own, without other help. Although active load handling can be realized by a robot arm mounted on the AGV, this AGV is not to resemble a mobile robot, so it is equipped with a conveyor belt that can be adapted to different transfer interfaces through a height-adjustable lifting device even during operation.

Vehicle control has to be distinguished from the coordinating control of the entire AGV that, according to [7], serves for coordinating several AGVs and/or integrating the AGV into the internal workflows. The coordinating control carries out the entire communication of the vehicle (e.g., receiving and confirming transportation orders) and handles driving functions, energy management, and safety aspects. For realizing these functions, the AGV disposes of a multitude of sensors and actuators.

An important component of the AGV is data transmission that enables communication between the coordinating control and the AGV. Via this communication information on transportation orders, vehicle position, battery state, error messages, and much more besides are exchanged.

B. Functions of an AGV for Order-acceptance Decision

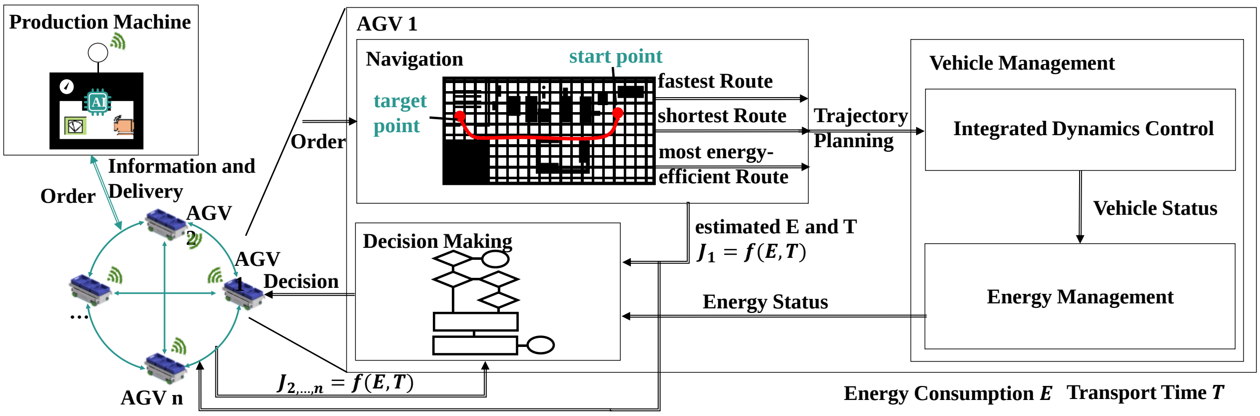

Figure 4. Decentralized self-optimized order decision of an AGV.

Fig. 4 all essential functions of the information processing of an AGV for realizing the decentralized decision-making on an order to be placed. In the following the individual functions and their interfaces will be described:

- **Navigation:** The most effective route for the AGV is determined on the basis of its current position with the aim of reaching an order-defined target position by means of Dijkstra's algorithm. Here, "effective" means a minimization of time and energy required for fulfilling an order within the limits set by the AGV's particular targets and the targets of the entire production line. Dijkstra's algorithm is based on graph theory, with the entire route network being described by a multitude of nodes and weighted edges. Depending on the destination the costs can be determined by taking into account track length, travel time, or energy consumption, and thus the search for the shortest and most time- or energy-efficient route can be started.
- **Energy Management:** The complete monitoring of the energy supply is integrated in the energy-management system (e.g., the load management of the battery). For securing goods transport, the energy management ensures a needs- and priority-based allocation of the electric power that is only limitedly available in the AGV. The underlying battery-management system monitors the actual states of the battery pack (e.g., state of charge and state of health). On this basis it can distribute the energy within the AGV and make this information available for order-acceptance decision.
- **Integrated Dynamics Control:** Via the integrated dynamics control the trajectory for executing an order is realized. It is generated from the route determined by the navigation. This control serves for reaching the target position defined in the transportation order.
- **Order-acceptance decision:** Order-acceptance decision is one of the core functions of an AGV and also an essential process in supporting the production flow. It is made by means of artificial intelligence in combination with machine-learning methods. On the basis of the route determined by the navigation function, transportation time T and energy consumption E can be estimated for this order. Energy management provides the current energy state of the AGV that is also factored into the decision whether to accept a transportation order. If the state of charge of the battery is too low or the AGV has not enough energy left for fulfilling the transportation order, the AGV can report this to the other AGVs and does not have to be involved in the further decision process. In case the battery has sufficient energy, the costs J are computed in consideration of the weighting factors (a und b) for scaling the variables T and E as follows:

$$J = aT + bE \qquad (1)$$

via the communication module (e.g., based on WLAN) the AGVs can compare costs and select the AGV incurring the smallest expenses for taking over the order.

V. Simulation and Results

In this section an exemplary scenario will be presented that illustrates the function of the decentralized order-acceptance decision enabled by the IoT-based communication of the AGVs.

A. *Exemplary Scenario*

Assume that a production machine has completed work on a product. It then communicates with the AGVs via WLAN and places a transportation order so as to make one of the AGVs transport the product to a storage location or to another production machine. In view of the target position of the order, the AGVs use their navigation function to find a route between their current position and the target point. As described above, transportation time and energy consumption of the AGV are estimated for this route. Artificial intelligence is then used for computing costs for this order, thus providing a basis for joint decision making.

B. *Simulation Results*

Simulation is based on the following assumptions:

- Every AGV can only execute one order at a time and move at a constant velocity.
- All AGVs have a battery state-of-charge that is sufficiently high for executing the order.
- The delay in the exchange of information between the AGVs themselves and between them and a production machine can be neglected.
- Dynamical obstacles such as factory staff or other AGVs will not cross the route of an AGV so that there will be no need for unpredicted sub-calculations during execution of a transportation order.
- The production hall is even with the ground and has no ascending slopes.

Fig. 5 displays the simulation result of an ATS with three AGVs. In this example the production hall is quadratic and delimited by walls (black lines). The black surfaces in the production hall represent areas that are impassable because of obstacles. Furthermore, it shows the shortest routes from its position to a target point that every AGV has gathered from its own navigation function.

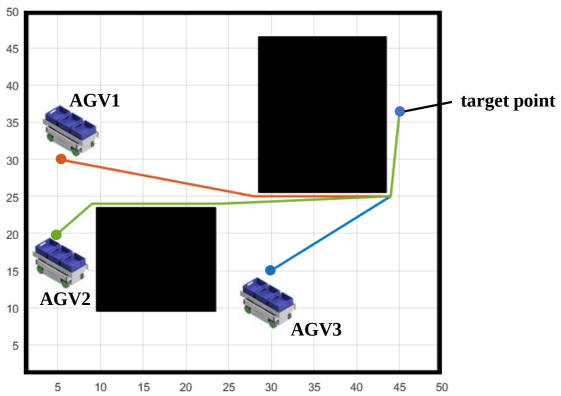

Figure 5. Shortest route of an AGV to its respective target point.

The distances of the routes of the three AGVs are listed in Table I. Assuming the velocity to be constant, transportation time is calculated for the route. Due to identical motion speeds of all AGVs their energy consumption can be neglected as it is always proportional to the transportation time; thus transport costs on the routes are sufficiently described in accordance with the transportation time. In this scenario, because of its cost-effectiveness due to the shortest transportation time, AGV3 has been selected to execute this order so it can report order acceptance and the estimated transportation time to the production machine, thus allowing the latter to self-organize its further activities.

TABLE I. Distance and Transportation Time of the Routes of the Respective AGV.

	AGV1	AGV2	AGV3
Distance [m]	50,6	51,7	28,3
Transportation time [s]	63,2	64,7	35,3

VI. Conclusion and Future Works

The paper detailed the modular structuring and hierarchical ordering of an IoT-based production facility in the context of I4.0 as well as the integration of AGVs by means of digital interconnection, with decentralized order-acceptance decision as an example.

On the basis of the description of up-to-date, highly automated production facilities and of the AGVs employed by the industry, specifications for an autonomous production facility were identified.

These specifications served as a basis for deriving the communication- and interaction mechanisms between AGVs themselves and between production machines and AGVs with regard to realizing decentralized order-acceptance decision. For an AGV to make its own decision for a transportation order, its individual functions and their interaction were presented and illustrated by an exemplary application.

Future work will deal with developing algorithms for realizing the decentralized order-acceptance decision that will then be integrated into a real vehicle prototype and tested as well as further optimized under real-time conditions.

Conflict of Interest

The authors declare no conflict of interest.

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