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Decentralized control of logistic processes in cyber-physical production systems at the example of ESB Logistics Learning Factory

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Abstract

The increasing emergence of cyber-physical systems (CPS) and a global crosslinking of these CPS to cyber-physical production systems (CPPS) are leading to fundamental changes of future work and logistic systems requiring innovative methods to plan, control and monitor changeable production systems and new forms of human-machine-collaboration. Particularly logistic systems have to obey the versatility of CPPS and will be transferred to so-called cyber physical logistic systems, since the logistical networks will underlie the requirements of constant changes initiated by changeable production systems. This development is driven and enhanced by increasingly volatile and globalized market and manufacturing environments combined with a high demand for individualized products and services. Also nowadays mainly used centralized control systems are pushed to their limits regarding their abilities to deal with the arising complexity to plan, control and monitor changeable work and logistic systems. Decentralized control systems bear the potential to cope with these challenges by distributing the required operations on various nodes of the resulting decentralized control system.

Learning factories, like the ESB Logistics Learning Factory at ESB Business School (Reutlingen University), provide a wide range of possibilities to develop new methods and innovative technical solutions in a risk-free and close-to-reality factory environment and to transfer knowledge as well as specific competences into the training of students and professionals. To intensify the research and training activities in the field of future work and logistics systems, ESB Business School is transferring its existing production system into a CPPS involving decentralized planning, control and monitoring methods and systems, human-machine-collaboration as well as technical assistance systems for changeable work and logistics systems.

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1. Introduction

Future global market and manufacturing environments will be characterized by customized products resulting in small lot sizes and the demand for changeable production systems which allow the production of small lot sizes under the cost and performance conditions of today's mass production by a dynamic adjustment of production and logistics processes [1]. To cope with these future challenges scientists as well as experts and decision-makers from industry agree on the huge potential of the systematic introduction of enabler technologies like information and communication technologies summarized under the terms "Industrie 4.0" and "Internet of Things" [2] [3]. In addition fundamental changes regarding the technical infrastructure and IT-systems to plan, control and monitor changeable production systems are expected. Considering logistics, logistics networks including their logistics nodes have to keep pace with changeable production and value chain systems, which usually excludes the use of conventional logistics infrastructure like statically installed and centrally controlled conveyor systems and IT-systems which rely on predefined processes, leading to autonomous networks of CPS which are decentrally controlled and enable changeable logistical processes [1] [4]. Besides extensive process-related changes these evolution will also result in substantial investments why the transition period is expected to last at least one decade and every company will have to develop individual and customized transition concepts in cooperation with their

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value chain partners [5][6]. To plan, design and control changeable production systems as well as to transfer existing production systems into changeable production systems and to derive customized transition concepts specific knowledge and competences are needed [7]. To ensure a smooth transfer into industrial practice, newly developed methods and technical solutions have to be tested and validated in a safe and at the same time practice-oriented factory environment. Learning factories, like the ESB Logistics Learning Factory at ESB Business School (Reutlingen University), offer a wide range of possibilities for an interdisciplinary research in the field of cyber-physical production systems as well as many options for a practice-oriented education and training of students and professionals in a close-to-reality factory environment. Based on defined maturity levels of the learning factory, the participants can be sensitized and trained in the field of cyber-physical systems including innovative planning, design and control methods and at the same time gain specific competences.

2. Decentralized control in cyber-physical production systems

Future production environments and supply chains will be highly influenced by a global cross-linking of all machineries, storage systems and means of production to cyber-physical systems (CPS) respectively cyber-physical production systems (CPPS) [1] [8]. CPPS are networks of independent CPS creating a comprehensive, dynamic and changeable production system based on a high degree of cross-linking of all involved systems representing an autonomous and intelligent production unit [9]. CPPS also have to be capable of analyzing data in real-time and to make decisions autonomously or via hybrid decision making processes as an interactive human-machine decision finding procedure using the specific capabilities of humans and CPS in a synergetic manner to interact actively with humans as well as other digital and physical objects linked to the Internet of Things and Services [10]. These vertically cross-linked and integrated production systems are crucial elements of the resulting horizontally integrated and real-time optimized value chain networks based on digital consistent engineering processes incorporating the entire product and factory life cycle of value chains [7][9]. In order to meet these challenges data, services and specific functions will be held, retrieved and executed where the highest benefit or performance can be achieved, which will not necessarily be on the conventional automation levels. On that assumption, today’s predominantly found hierarchically structured automation pyramids will be resolved and replaced by interconnected, decentralized automation systems. The services, data and hardware components of the emerging decentralized automation system will be spread over various nodes of the dynamic network creating abstract functional modules [11].

2.1. Value chain networks

Value chain networks in CPPS will be affected by a dynamic and horizontal integration of value chain elements of the CPPS which organize, optimize and execute themselves ad-hoc. Major enablers for this development are intelligent products respectively logistical objects, which know and communicate their current status and location, know their target destinations within the value chain and control the required production and logistics processes actively [12]. Therefore a cross-functional digitalization and link-up of value networks down to the field level is of vital importance. For example in a Industrie 4.0 scenario the purchasing department will be able to track inventories in the own company as well as in the supply network in real-time to keep production running, while the customer will be able to keep track of the degree of completion of his individualized product. So the field of view of companies will change from the boundaries of their own factories to the whole value network involving all processes and partners from the engineering, sourcing, production up to the delivery of the final product to the customer. For an efficient and dynamic exchange of information within ad-hoc designed value chain networks standards and reference architectures are required [13]. Also new methods and processes regarding the use of big data to identify customer needs, predictive maintenance for machineries, the use of open-innovation principles and collaborative engineering to produce products which meet the customer needs and new methods how value chains are decentrally designed, organized and controlled as well as costs and earnings are allocated within this dynamic value chains have to be developed [14] [15].

2.2. Intralogistics systems

The planning and control of highly dynamic and changeable material flows of CPPS require new methods and systems, since a regulation and reconfiguration of the material flow will be required at any point of the material flow system [4]. Today’s centrally controlled material flow systems using centralized material flow computers are not capable of accommodating future requirements of tailor-made products, decreasing batch sizes and volatile sales and procurement markets, because these system rely on complex, centralized controller architectures which are neither flexible nor changeable [16]. The combination of changeable production systems and conventional control approaches based on predefined processes would result in a tremendous increase of complexity and a continuous programming effort of central control units like material flow computers [17]. In addition small production batches up to batch size 1 are leading to an increasing number of transport orders which have to be processed and a high complexity of the control systems [18]. The development of decentralized control concepts for automated material flow systems combined with the theories of the Internet of Things offer great potential to solve the previously mentioned weaknesses of centralized control systems regarding changeable application scenarios in context with changeable production scenarios 4.0 [17]. The basic units of the Internet of Things are cooperating functional units (entities) of conveyor modules, transport units and (software) services which define every automated material flow system [17] [19]. So the goods which have to be transported, route themselves autonomously through the logistical system by using the transport services of the conveyor modules to reach their destination and can be identified and localized anytime within the material flow system. By refraining from the use of centralized material flow computers the complexity of the system can be reduced while the versatility and responsiveness of the material flow system can be highly improved. In addition the solving of arising interruptions and blockades as well as an automated replanning and rescheduling of transport processes and routes are becoming inherent functions of the material flow system [16] [17]. Multi-agent systems, which consist of autonomous and cooperating software programs (agents) solving specific tasks based on defined behavior patterns, are the most common base technology besides other natural analog models for the realization of these decentralized material flow control systems.

So, for example, each conveyor module uses one or more of these agents for a dynamic processing of different tasks like order management, order allocation or route planning depending on the current situation and condition of the logistics system [19]. In addition these agents have to conduct target management to deal with conflicting goals and should be designed in that way, that the quality of their behavior and their decisions improve continuously by taking previously made decisions and system's behavior into account [20]. This continuous, proactive and iterative improvement and adaption of systems and structures combined with the capability of solving parallel problem domains are major characteristics of autonomous controlled systems [10] [21]. Based on these capabilities the logistic objects perform information processing tasks, decision-making and the execution of the made decisions autonomously within the respective system environment. By using these principles, the dynamic and structural complexity of horizontally and vertically cross-linked logistical systems can be mastered also with limited information [22]. In addition a higher robustness and positive emergence of the entire system can be accomplished by a distributed and flexible handling of the dynamic and complexity of changeable logistic systems [23].

In General the control functions formerly found in a centralized, hierarchically structured automation pyramid are transformed into a non-hierarchical material flow system composed of cooperative, intelligent and autonomous entities in the Internet of Things. By means of their agents these entities are capable of contacting other conveyor systems, transportation entities and services, are able to exchange and process information and finally to organize and control the material flow autonomously in an optimized manner [16] [17]. Conveyor systems, like the "FlexConveyor" of the company Gebhardt Fördersysteme GmbH, which are following this modular concept mechanically as well as regarding their control systems, are already in industrial application and allow a fast reconfiguration of the conveyor system according to recent requirements.

3. ESB Logistics Learning Factory

Learning factories in the narrow sense cover a real value chain including a physical product which enables researchers, students and training participants in general to perform, evaluate and reflect their own actions in a close-to-reality research and learning environment [24]. Learning factories also offer a wide range of possibilities for industry-oriented research projects, training of professionals in various disciplines and an immersive, interdisciplinary and practice-oriented education of students.

3.1. Production system

The overall objective of the ESB Logistics Learning factory (LLF) at Reutlingen University is to educate and train students and professionals from industry specific competences required for the design and optimization of changeable production systems also in context with new requirements of CPPS and emerging decentralized control methods. The production system is focused on the assembly of a multi-variant city scooter including the use of innovative planning and control methods for production and intralogistics, technical assistance systems and additive manufacturing technologies. All workstations and logistics infrastructure are mobile to allow an easy change of the factory layout and all workstations are provided with tablet-pcs using wireless communication technology for bidirectional information exchange between the shopfloor level and the digital planning environment as well as to access multimedia-based work instructions. The access and feedback of information can be designed manual as well as automated using different maturity levels of information technology, e.g. RFID-technology embedded on the product or microcontroller-based digital devices equipped with communication technology and sensors on the product, to gather and exchange data with other objects and to act as intelligent objects in the Internet of Things. These technologies serve as major enablers in the LLF for the development of a decentralized control system in which the product routes itself autonomously through the production system.

3.2. Framework for decentralized control systems

The SES architecture, which is based on an event-oriented concept enriched with a specific cloud data-storage structure for central and decentral system entities, serves as a framework for the development of decentralized control methods within the LLF. A simplified structure of the SES approach is shown in figure 1. In general the system is composed of "system-related nodes and objects" and "scenario-specific nodes" which provide different services to enable decentralized control and decision-making. The term "nodes" is standing for autonomous software agents providing specific services and interacting with other agents within the production system. For example agents found in the level "system-related nodes and objects" cover amongst other things functionalities respectively services usually found in conventional Manufacturing Execution Systems, like order management, prioritization of production orders and specific production control functions as well as services to integrate different kind of IT-systems, infrastructure and resources. A major advantage of this approach compared to conventional (MES) system approaches, besides the ability to cope with the complexity resulting from the changeable production system of the LLF, is that the functional range of the SES can be extended easily and stepwise by modelling additional agents covering different functionalities and/or representing (cyber-physical) infrastructure elements due to its open architecture. Also scenario-specific nodes for additional resources like workers, collaborative robots or workstations offering specific (assembly) services can be modeled and integrated as well as conventional centralized systems or system functionalities can be transferred into the decentralized planning and control of the SES based on the developed framework.

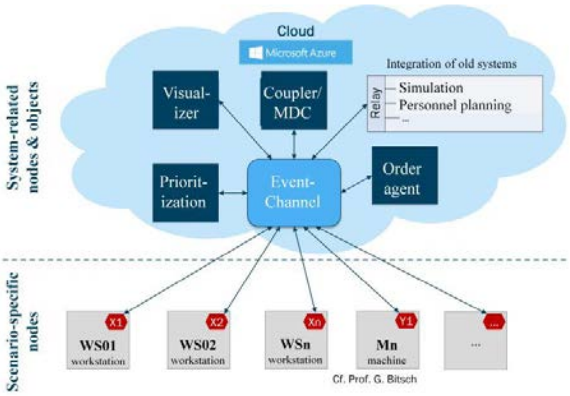

Fig. 1 Basic structure of SES

Various projects within the LLF have shown the huge potential of this system approach in context with changeable production scenarios. Nevertheless the SES is still in the proof-of-concept phase and a major content and enabler for further research in the field of decentralized production planning and control at the LLF.

3.3. Decentralized control of intralogistics processes

The intralogistics system at the LLF contains various types of transport systems reaching from manual pallet trucks and transport trolleys up to autonomous guided vehicles (AGVs) and an intelligent, decentrally controlled continuous conveyor system. The routing and navigation of the AGVs is based on optical tracks or 2D-laser-sensors to allow flexible factory layouts. The modular and decentrally controlled conveyor system “FlexConveyor” supplied by the company “Gebhardt Fördersysteme” is a good example for a CPS implantation for intralogistics at the LLF. The modules of this conveyor system, with decentralized control units in each conveyor module, can be combined to user-defined conveyor lines based on their “plug-and-convey” functionality.

In the medium term, the intralogistics system at the LLF will be further developed into an autonomous, decentrally controlled and changeable logistics system composed of intelligent bins and products, centrally and decentrally controlled conveyor systems and software services respective software agents based on the SES approach serving as a practice-oriented environment for various additional research projects as well as for trainings and educational use.

Based on a multiagent system approach, the existing infrastructure will be enriched with additional sensors as well as computing and information processing capabilities to enable decentralized control methods. Starting with an intelligent product memory a control system will be developed in which the product communicates with other CPS in the assembly and logistics system of the LLF like workstations, supermarket racks and different transport systems e.g. to check for available resources for specific assembly operations at the workstations and for related material supply demands which have to be fulfilled by the cyber physical logistics system to execute the assembly. The current approach for the modelling of software agents based on sub-models and specific entity attributes is illustrated in figure 2 at the example of an intelligent bin which is capable of communicating with other CPS respectively software agents to fulfill specific tasks and to reach entity specific objectives in line with the superior goals of the production system (e.g. lead time, security of supply) autonomously based on the interaction with other entities within the production system. By means of this approach in combination with the SES framework an autonomous real-time capable and objective related configuration of the logistics system based on the available infrastructure should be achieved. Besides the optimized use and combination of different conveyor systems, an optimized collaboration of humans and technical assistances systems for material supply processes as well as for decision making processes (e.g. hybrid decision making) will be investigated within the cyber physical logistics system at the LLF.

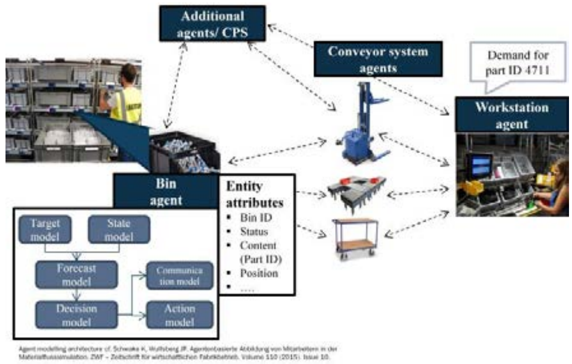

Fig. 2 Cyber physical logistics system

3.4. Collaborative, decentrally controlled tugger train transport system

To investigate the potential for automation and/or human-machine collaboration in changeable material flow systems in context with future CPPS, Reutlingen University will launch a research project to develop a collaborative tugger train system in close cooperation with industry partners which will be funded by the Federal Ministry of Education and Research. The fundamental aim of this research project is to develop an interactive, collaborative and autonomous tugger train system which is capable of navigating through complex and changeable factory environments, is able to handle different goods and bins and has to be integrated into the decentrally controlled production system of the LLF. The towing vehicle of this tugger train is a robot platform using laser scanners for navigation which is equipped with a collaborative articulated-arm robot on its top to manipulate goods, e.g. to load goods from the supermarket racks onto the trailers of the tugger train. So the advantages of tugger trains compared to other means of transport, like safety, productivity and flexibility, should be combined with the potentials of automated material supply, human-machine collaboration and the event-oriented and cloud-based concept of the SES framework to develop a specific decentralized control method for the tugger train system in combination with the intelligent objects in the production system of the LLF. Building on the findings of this research project as well as on the above mentioned development of a cyber physical logistics system based on intelligent objects and software agents, a generic method for an autonomous and decentralized control of changeable hybrid intralogistics systems will be developed within a dissertation project at Reutlingen University. In the long run an autonomous and decentralized control method for changeable production systems should be developed and validated at the LLF, resulting in a scenario in which all goods route themselves autonomously through the production system of the LLF by using the available resources of the CPPS in an optimized manner.

4. Conclusion

The cross-linking of different entities and CPS within factories and entire value chain networks is leading to new challenges regarding the planning, control and monitoring of these changeable systems. To cope with the arising complexity decentralized systems which foster autonomous and local decision-making are a promising approach. Also reference architecture models, like the RAMI4.0 reference architecture model [13] which is based on existing standards, are of great importance to identify further fields of research and standardization needs for the establishment of CPPS.

Over the next years the digital and physical learning factory environment of the LLF will be gradually transferred into a cross-linked, decentrally controlled CPPS to serve as an education, training, research and demonstration environment for CPPS-related technologies and methods. Major research priorities of the LLF are the development of decentralized control methods for production, assembly and logistics processes as well as innovative human-machine collaboration methods for work and logistics systems which will be developed, tested and validated under close-to-reality conditions in the LLF. The next step for the development of a generic method for an autonomous and decentralized control of changeable hybrid intralogistics systems is the definition of the logistical system model, the system components and the system boundaries. Based on these results the further steps, like the generation of data models and the design of a specific decision model, will be derived.

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