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Development of an Experimental Environment to Study the Challenges in Cyber-Physical Intralogistics Systems

Entwicklung einer Versuchsumgebung zur Untersuchung der Herausforderungen in cyber-physischen Intralogistiksystemen

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The trend towards heterogeneous, decentral systems in intralogistics results in the need for a concept to describe and virtualize assets to enable their interaction. The multi-layer concept of Cyber-Physical Intralogistics Systems (CPIS) is introduced. The system description (*descriptive layer*) defines the structure of the digital twins and the communication (*virtual layer*) of physical (robots, periphery) and logical assets (control systems, simulations). To implement this concept, an experimental environment was developed at the Institute for Material Handling and Logistics and the Karlsruhe Institute of Technology. It consists of physical components, such as models of mobile robots or manipulators, and further periphery, such as racks and charging stations. The environment is supplemented by simulations and control software.

Use cases for CPIS are to be implemented and tested in this environment. Due to the easily accessible hardware components and the possible scaling of the systems in the simulation, implementation cycles can be reduced, and results can be achieved quickly without requiring a real-world intralogistics system. CPIS can be used to initialize an automated charging process or to exchange perceived position data of system participants. The primary goal is to enable a modular system, add new participants through plug-and-play, and make systems easily changeable.

[Keywords: Cyber-Physical Intralogistics Systems, Intralogistics, Industry 4.0, Cyber-Physical Production Systems, Changeability]

Der Trend zu heterogenen, dezentralen Systemen in der Intralogistik erfordert ein Konzept zur Beschreibung und Virtualisierung von Assets, um deren Interaktion zu ermöglichen. Das mehrschichtige Konzept der Cyber-Physical Intralogistics Systems wird eingeführt. Die Systembeschreibung (*Descriptive Layer*) definiert die Struktur der digitalen Zwillinge und der Kommunikation (*Virtual Layer*) von physischen (Roboter, Peripherie) und logischen Assets (Steuerungssysteme, Simulationen). Zur Umsetzung dieses Konzepts wurde am Institut für Fördertechnik und Logistiksysteme des Karlsruher Instituts für Technologie eine Versuchsumgebung entwickelt. Sie besteht aus physischen Komponenten, wie den Modellen mobiler Roboter oder Manipulatoren, und anderen intralogistischen Komponenten, wie Regalen und Ladestationen. Ergänzt wird die Umgebung durch Simulationen und Steuerungssoftware.

In dieser Umgebung sollen Anwendungsfälle für CPIS implementiert und getestet werden. Durch die leicht zugänglichen Hardwarekomponenten und die mögliche Skalierung der Systeme in der Simulation können Implementierungszyklen verkürzt und Ergebnisse schnell erzielt werden, ohne dass eine reales Intralogistiksystem benötigt wird. CPIS können zur Initialisierung eines automatisierten Ladevorgangs oder zum Austausch von Positionsdaten aufgenommen durch Systemteilnehmer genutzt werden. Das primäre Ziel ist es, ein modulares System zu ermöglichen, neue Teilnehmer durch Plug-and-Play hinzuzufügen und Systeme wandelbar zu machen.

[Schlüsselwörter: Cyber-Physical Intralogistics Systems, Intralogistik, Industrie 4.0, Cyber-Physical Production Systems, Wandelbarkeit]

1 INTRODUCTION

Today, companies can only stand out from the competition if they are able to react to external influences such as changes in demand or delays in supply chains on a short-term basis. Possessing and managing this ability to change is one of the main challenges of the *Industry 4.0* movement [1]. While flexibility is the ability to react to changes with existing resources, changeability is the ability of a system to adapt to new requirements by modifying or scaling the resources [2]. The characteristics of these so called cyber-physical production systems (CPPS) are able to provide this changeability [3] through their ability to

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collect information, connecting to other system components and respond to internal and external changes [4]. Through CPPS, a shift from the classic hierarchical production systems to a distributed system consisting of CPS is currently taking place [5]. Several government programs are introduced to advance CPPS like *Industry 4.0 in Germany* or *Smart Manufacturing* in the United States [6].

Since this change is taking place throughout production, intralogistics is also affected and has a critical role, since it is a non-value adding process, the costs of changes must be as low as possible [7]. Intralogistics encompasses the organization, control, execution and optimization of internal material flow [8]. Concepts like *Logistics 4.0* [9] and Cyber Physical Logistics Systems (CPLS) [10] are mainly focusing on the use of *Industry 4.0* and CPS in the context of the complete supply chain and the logistics network not on intralogistics. This paper, on the other hand, is focusing on technical solutions for automation by the use of robots in intralogistics processes.

Small and medium-sized enterprises would especially benefit from an easy, low-cost integration of AGVs in their production. It can increase the flexibility of intralogistics processes by relieving employees and reducing transport errors [11]. Integrating industry 4.0 and CPS in intralogistics always means to deal with brownfield development. There are automated subsystems like storage and retrieval systems (AS/RS), conveyors or Automated Guided Vehicles (AGVs) working together with manual processes like forklift drivers or commissioning. Most of these systems have their own proprietary control system [12].

Characteristics of CPS can be transferred to intralogistics systems, since systems of heterogeneous, intelligent participants must communicate and interoperate. Modularity and the use of a digital twin are the key to scalable and changeable systems [1]. Examples to deal with this paradigm shift form a hierarchical to an interconnected system are autonomous intralogistics systems with the ability to plan, execute and optimize processes in an decentralized manner [13] and Cyber-Physical Transport Modules (CPTM), a interoperable interface for AGVs with Industry 4.0 characteristics [7].

An experimental environment was developed at the Institute for Materials Handling and Logistics Systems at the Karlsruhe Institute of Technology to investigate heterogeneous multi-robot systems and their interaction with other participants in intralogistics. Use-Cases can be implemented both in a physical environment with the help of various model robots and in a virtual environment through physics-based simulations. The model robots have different capabilities for localization, navigation, and transportation. The simulation has the advantage of upscaling the number of robots and investigating algorithms with a high robot count. Through this, it is possible to test *Industry 4.0* concepts not only with one mobile robot and two transfer stations, but with a whole (model) factory.

In Chapter 2 the concept for Cyber-Physical Intralogistics Systems is introduced and the experimental environment is presented, on which use-cases for the CPIS can be implemented and tested. The core components of CPIS are described in Chapter 3. In Chapter 4, the two use-cases *Localization and Tracking of Assets* and *Automated Charging Processes* are presented in detail while several others are listed as an outlook.

2 CONCEPT OVERVIEW

2.1 CYBER-PHYSICAL INTRALOGISTICS SYSTEMS

This paper introduces the term Cyber-Physical Intralogistics Systems (CPIS) as a subset of CPPS. CPIS include all systems and peripheral devices that plan, execute, and optimize intralogistics tasks. This includes, for example, transport systems such as AGVs, conveyors or handling robots, but also transfer stations or charging infrastructure systems. The CPIS is not restricted to physical assets, but also includes logical assets, like control systems and simulations.

At the lowest level there are the physical and logical entities. Physical entities are hardware that is existing in the real world. Logical assets are entities that make decisions based on external influence. Each of these entities has a virtual representation. The properties of each asset are summarized on the cyber level by a virtual representation. On the cyber level, there is also the interface of each entity. This interface should represent all communication that is necessary between the system components. Communication between the cyber-physical systems that are components of each entity are handled inside each asset. For this communication, the physical and logical assets are black boxes, that only provide the necessary information in their virtual representation. There is also an information flow back into the physical or logical asset from its virtual representation through function calls from other entities. This structure represents a decentralized system, because there is no hierarchical structure, but information flow is happening on the same level and decisions are made inside the black boxes. At the highest level, there is the descriptive layer. Here the structure of each asset is defined. To create a modular system, it is necessary to know how to communicate with assets of a certain type (definition of the interface).

2.2 EXPERIMENTAL ENVIRONMENT

CPIS are representing all entities connected to intralogistics processes. In this paper an experimental environment is presented that is a model of a real world

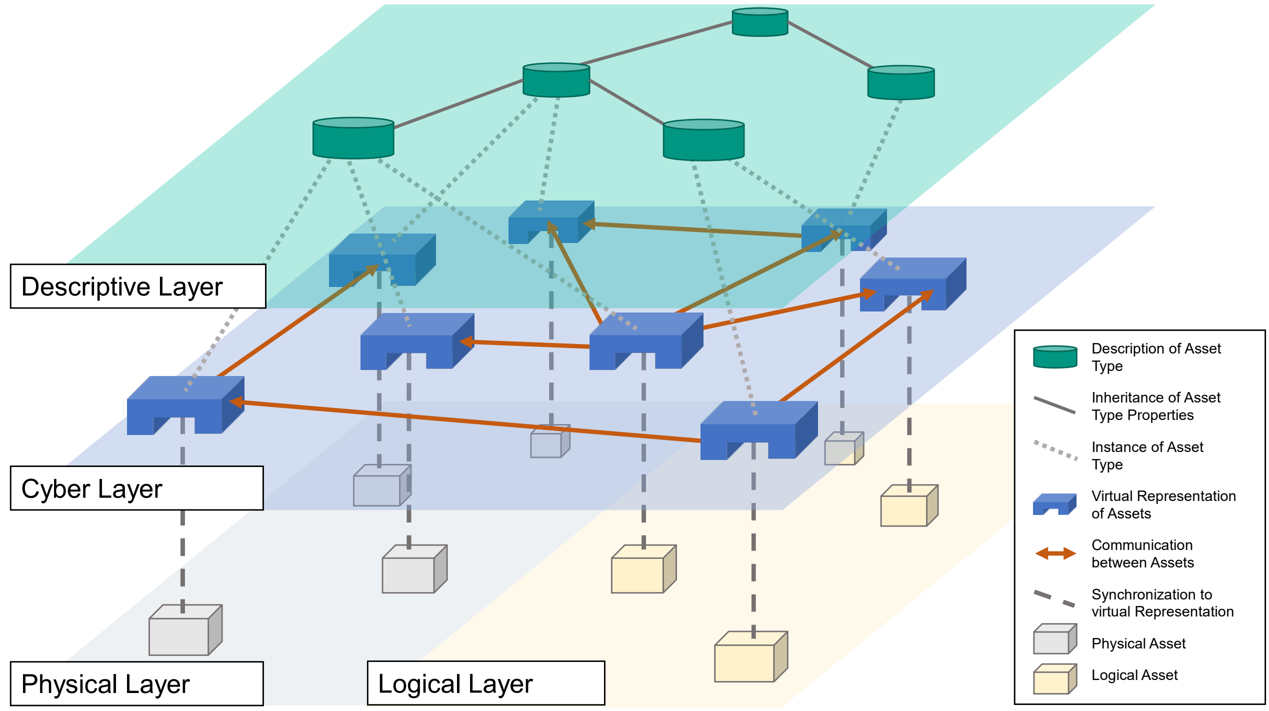

Figure 1.: Concept of a Cyber-Physical Intralogistics System composed out of physical and logical entities, their cyber counter part responsible for interaction with other participants. The structure of each participant is defined in the descriptive space [1].

CPIS. The physical part of the demonstrator is a six square meter platform build with six one by one-meter modules and a mounting structure to which sensors and visualization technology can be attached (see Figure 2). As shown on the bottom-left side in Figure 3 a set of model robots is used to represent the hardware used in CPIS. As representation of AGVs the model robots TurtleBots [14], a solid and commonly used model for movable robots. The TurtleBots can also represent other vehicle types, like forklift trucks by installing a lifting system and a liftable fork. mobile platform based on the Robot Operating System (ROS), are used [15]. These robots are able to use various sensors, such as lidar, camera-based navigation or pure odometry to determine position and path finding. The TurtleBots can also represent other vehicle types, like forklift trucks by installing a lifting system and a liftable fork. The periphery in form of conveyor and slider technology as well as manipulators, are created with models by the company ufactory [16], which are also based on ROS. The environment is supplemented by shelves and other static elements of intralogistics, such as transfer stations. Also, a system for automated charging of the robots is to be implemented. All physical components have a digital twin on the cyber layer. All the communication between system component takes place between the digital twins. Each digital twin is an instance of an asset type defined in the descriptive layer.

In addition to the physical components, logical components are a part of the experimental environment. A physics-based simulation of transfer and transport processes in the environment is implemented. This allows to scale up the number of robots to test algorithms with a high robot count. A fleet management system (FMS) as an example for a centralized control system will be implemented as well. As shown in Figure 3 the logical components are also an instance of an asset type. Since the simulated and the actual robot have the same structure definition, they can be exchanged seamlessly. In the context of CPIS, it does not matter whether a real robot or a logical asset in a simulation is controlled.

Figure 2.: Concept of the physical part of the CPIS experimental environment.

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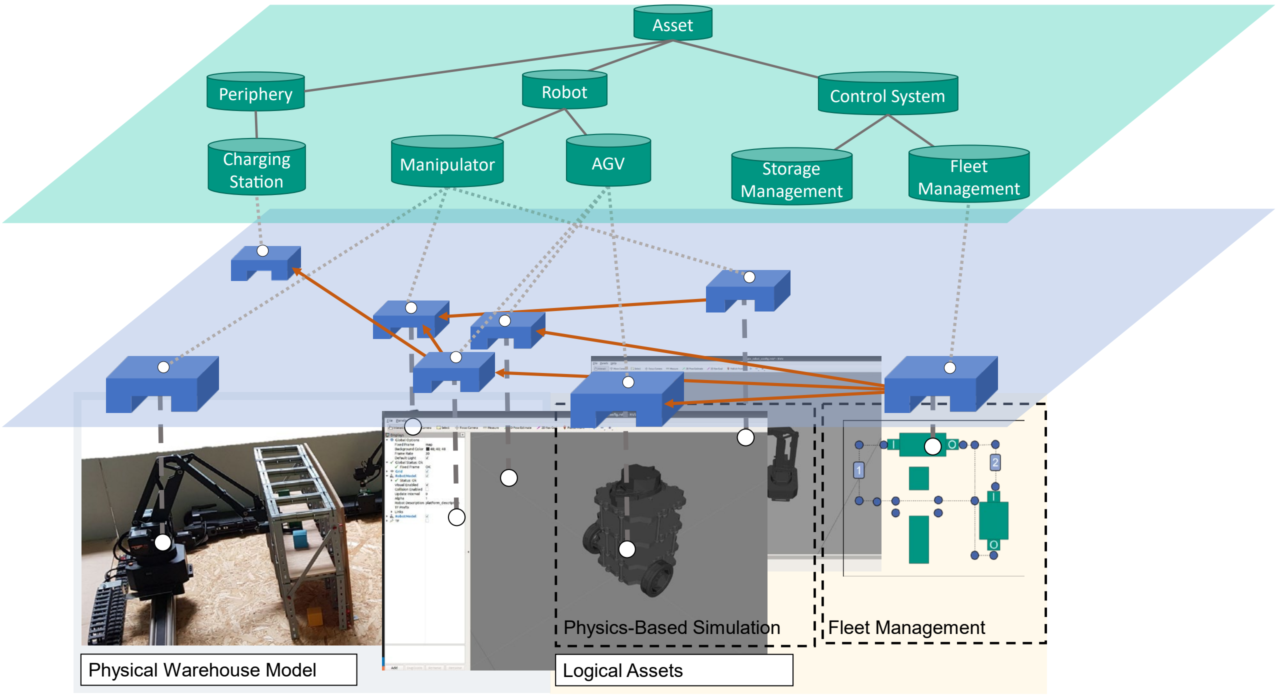

Figure 3.: Part of the realization of a CPIS in the experimental environment at the Karlsruhe Institute of Technology with a real-world warehouse model, a physical simulation of the robots and a fleet management system to control the physical and simulated AGVs (Based on [1]).

3 CPIS FEATURES

3.1 SYSTEM DESCRIPTION

To enable interoperability between assets in an interconnected system it is necessary to know how information of an asset can be accessed from outside the system. The descriptive layer is providing this information to the virtual representation of each asset. Several concepts for system description are present in current research. In this chapter the concept of ontology and the framework for modular material handling with decentralized control is presented.

3.1.1 USING AN ONTOLOGY TO DESCRIBE INTRALOGISTICS

An ontology, defined as a “formal, explicit specification of a shared conceptualization” [17], is a common way to describe concepts and relations of a specific domain. Negri et. al. conducted an extensive literature review about ontologies in the logistics domain [18]. The review showed that the majority of the found logistic ontologies focus on the supply chain level rather than on intralogistics. In addition, the few existing intralogistics ontologies mainly focus on modelling processes rather than on resources. To our knowledge, Knoll et. al. provide the most comprehensive intralogistics ontology [19]. It features concepts like material flow resources, processes, activities, unit loads, etc. However, the presented ontology was developed to support process mining, while our goal is to create a common knowledgebase for autonomous entities. This knowledgebase should in the future be able to answer extensive queries, e.g., “Which unit load can I transport?”, or “At which transfer unit can I dock at?”. The core concepts, in which intralogistics-specific concepts and relations can be integrated, is presented in [20].

3.1.2 BOTTOM-UP APPROACH

The *Framework for Modeling Material Handling with Decentralized Control* [21] aims at creating a truly flexible material handling system by using a bottom-up approach to describe processes from a finite set of elementary functions. Participants in these systems can process input and their perceived environment to make decisions. In this experimental environment these hypotheses are to be implemented and tested. Especially the characteristics of simple scaling and redesign are promising points to be explored in the Experimental Environment.

3.2 DIGITAL TWIN

The concept of *digital twins* has been widely used in many different domains resulting in many different definitions on what a digital twin represents. For the proposed architecture, we follow the definition by Van der Horn et al. who describe a digital twin as a *“virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual system”* [22]. This definition focuses on the bidirectional, automatic data flow between the physical and the digital object, which is the distinguishing feature compared to the concept of a digital model or a digital shadow [23]. In the presented experimental environment, digital twins are used to:

- provide static or dynamic data fields to other digital twins on the cyber layer,
- enable interactions between digital twins by means of function calls and event mechanisms.

However, the data structures of the digital twins must be standardized to allow interoperability. We therefore leverage the concept of the *asset administration shell* [24] combined with the ontology-based approached as discussed before.

3.3 COMMUNICATION

As shown in Figure 1 the change from a hierarchical to a completely interconnected system leads to many new interfaces that must be defined. Connections, that before never were necessary, like the direct interaction of an AGV with the Enterprise Resource Planning system becomes necessary because the decentral control can directly decide if, how and when an order is executed. The three most relevant types of communication for CPIS are central, partly decentral, and decentral communication.

Central communication equals the master-slave system, where exactly one slave can communicate with exactly one master, but one master can communicate with n slaves. A typical application for the central communication type is the data exchange between a fleet manager and n AGVs. The communication interface VDA5050 [25], for example, offers a manufacturer-independent communication standard for the central exchange of order data. Load and route descriptions are sent from the communication master of the FMS to the AGVs. In the opposite direction, status data of the AGVs are transmitted to the FMS.

Partly decentral communication allows one to one communication between two systems, but a central instance still exists. This is the case for fleet managers, for example, where current route availability or transport orders are shared centrally. However, the distribution of transport orders and the planning of routes can be performed decentral.

For all of these communication types it is necessary to know how to talk to each other. If a custom interface is necessary for each asset in the system true flexibility and scalability will never be reached. But if the interface is described in the descriptive layer, new participants just have to fulfill this interface and they can interact with every other asset in the system by plug-and-play. Existing systems can even be integrated into CPIS by updating the controller.

Common protocols such as OPC-UA, ROS or MQTT are well suited for decentralized communication since these communication protocols work according to the publisher-subscriber or server-client principles.

4 CPIS USE-CASES

4.1 LOCALIZATION AND TRACKING OF ASSETS

In CPISs, knowledge about the location of assets like AGVs or unit loads are important information that are increasingly dynamic in flexible systems. By knowing where a certain product currently is, concepts like batch size one and individualized products becomes possible. A CPIS consists of physical assets with very different perception capabilities, varying from systems that can only sense the existence of a physical object by means of a laser beam to sophisticated systems which run AI-based object detectors and pose estimators. However, all assets can combine their knowledge to create a proprioception for the CPIS itself. This idea is being investigated in PropS, *a proprioception system in CPPS by means of collaborative localization* which has the idea to gather and use distributed pose information provided by intelligent assets to form a combined pose graph [26].

PropS itself can be categorized as a logical asset, according to Figure 1, and its DT does:

- periodically create a connection to all other DTs,
- scan their applicability as a provider of pose information by searching a specified *AAS submodel,*
- read their locally provided pose information to integrate it in a global graph,
- offer methods to the other DTs to request pose information between a given set of reference frames.

In dynamic environments, PropS enables less sophisticated assets to use pose information of the current system state which can be used in many different scenarios.

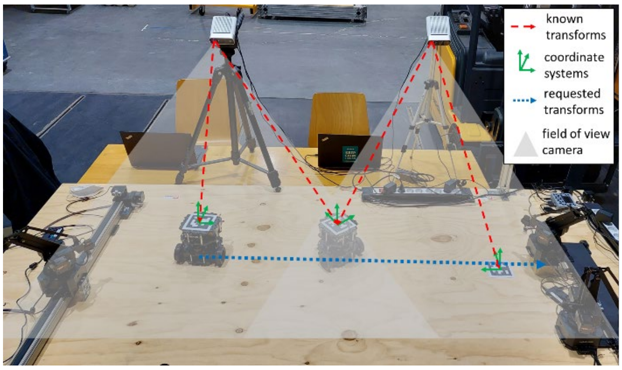

Figure 4.: Concept of PropS visualized on physical components of the CPIS experimental environment [26].

Figure 4 shows one exemplary application in which a mobile robot requests the goal pose for a material handover with a manipulator with respect to his own reference frame. PropS can resolve this request by combining the information provided by two camera systems, that use the pose of another mobile robot as an intermediate and linking reference point.

The presented experimental environment and its components will allow further investigations of PropS in different scenarios. Future challenges for PropS are summarized in [26].

4.2 AUTOMATED CHARGING PROCESS

Automated guided vehicle systems (AGVSs) make up a large share in current, flexible intralogistics. The mostly battery powered AGVs require regular charging processes for their energy storage system (ESS). Different strategies can be applied, e.g., by charging once after a specified period of operation, with brief intermediate charges during operation, or in cyclic operation [27, 28].

Current AGVSs usually have manufacturer-specific or even vehicle-specific charging infrastructure systems (CISs) which makes the charging processes manufacturer dependent as well. Vehicle control, energy storage system, energy transmission system and the charger are closely linked to each other and do not allow easy integration into existing CISs. Accordingly, communication and the charging process commonly dependent on the respective system solution.

The presented experimental environment is used to validate concepts for the description of charging processes of AGVs and the corresponding communication between a CIS and an AGV. The foundations of an approach are outlined in the following sections.

4.2.1 CHARGING PROCESS DATA COMMUNICATION

Communication at supervising level, e.g., the FMS, according to the automation pyramid [29–31] and systems at control level, e.g., AGV, CIS, ESS, can be divided at least into the three following communication concepts:

Figure 5.: Communication concepts for CIS in AGVS. Communication Level according to [29–31]

Abbr.	Comm. type	Comm. participants	Comm. Level
CC-C	central	CIS – FMS – AGV	supervising
CC-PD	partly decentral	CIS – FMS	supervising & control
CC-D	decentral	CIS – AGV	control

The first communication concept (CC-C) describes a central communication between CIS, FMS and AGV. While charging parameters and charging process data can be communicated between AGV and CIS, charging strategies can also be implemented at the FMS on supervising level. The CC-PD describes the partly decentral communication between the CIS and the FMS, whereas the AGV does not actively participate in the communication. Charging process data is provided by an FMS to the CIS depending on the AGV. The communication between the AGVs of a fleet can be decentralized. The third CC-D concept describes a fully decentralized communication between AGV and CIS, whereby charging parameters and charging process data are transmitted at the control level. This can be implemented either by a data carrier that provides the corresponding charging parameters of the ESS for the charging process by the AGV, e.g., by means of an RFID tag or a QR code, or by establishing an electrical communication between the AGV and the CIS.

For decentralized communication (CC-D), information about the AGV or its ESS must be transmitted to the CIS. If the data is actively sent from the vehicle controller, active bidirectional control of the charging process is possible. If bidirectional communication is omitted and unidirectional communication is implemented instead, this can simplify the technical implementation. This means that no adaptation of the vehicle control system is necessary since the software integration of the charging process is only carried out in the CIS. At the same time, this has the advantage of making it easier to integrate old AGVs into new environments (retrofitting) since only the provision of ESS data for the charging process is required. These can be stored, for example, in the form of a standardized data exchange format on a data carrier for decentralized charging processes or implemented as a standardized interface defined on descriptive layer according to Figure 1. The latter allows new components to add easily to the system.

4.2.2 CONCEPT OF A CHARGING PROCESS FOR HETEROGENEOUS AGV FLEETS

Figure 6 shows a concept of a charging process for AGVs with decentralized charging parameter communication. It is applicable for homogeneous as well as heterogeneous fleets which might use different ESSs. After the initial detection of a data carrier (1), the CIS can read the charging parameters of the respective AGV or its ESS (2) and subsequently set the parameters in the charging system (3). In the next step (4), the electrical connection is established either via electrical contacts or via a contactless energy transfer system. Once the electrical connection has been established, the charging process can be started by the CIS (5). In the final step, the charging process is automatically terminated either by the CIS when a defined termination criterion is reached or by the AGV leaving the

CIS and thus disconnecting the electrical connection (6). The charging parameters include, e.g., information on the final charging voltage, the maximum charging current, the minimum and maximum charging power, the charging curve and termination criteria.

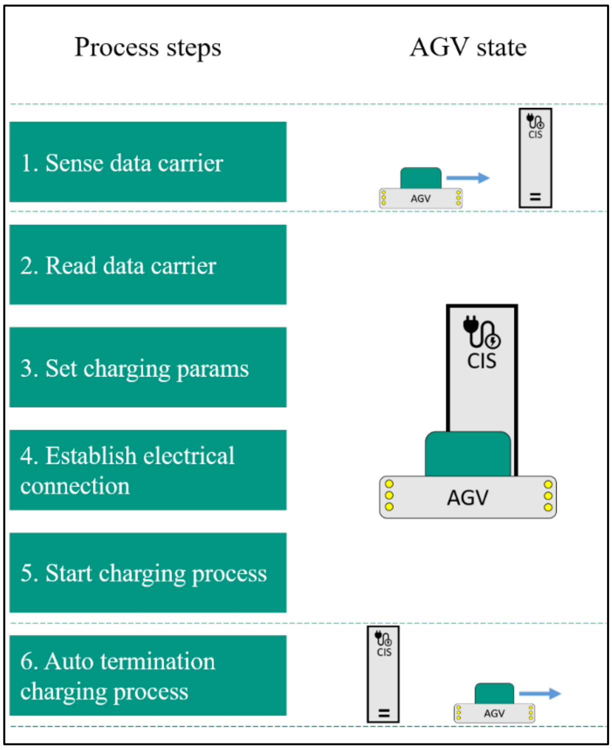

Figure 6.: Example of a charging process for decentral communication (cf. comm. Concept D). btw. AGV and read-only CIS. Right side describes the required driving states of the AGV during the process steps.

Known charging strategies for AGVS according to [27, 28] only consider systems consisting of homogeneous AGVs. Based on the previous consideration of homogeneous fleets, it can be assumed that the known charging strategies need to be extended to be applicable for heterogeneous fleets with different charging process requirements. For example, conditions for the allocation of CIS must be defined based on the technical parameters of CIS and AGV, which will increase the complexity of charging strategies depending on the number of different types of CIS and AGV.

4.2.3 HOW CAN A DIGITAL TWIN HELP?

As shown by Li et al., a digital twin can be used advantageously for the estimation of the state of charge (SoC) and the state of health (SoH) for ESS [32]. Adapted for use in AGVs, this can help optimize fleet scheduling. A case study by Han et al. showed a transport execution time reduction by 10.7% and a reduction by 1.32% in energy consumption [33]. Pires et al. demonstrated that a DT can also be used to optimize specific manufacturing costs in a production line by considering several route scenarios in a kind of "what-if simulation" by the DT, taking into account the number of AGVs as well as their ESS SoC, and evaluating them in near real-time [34].

According to the previously mentioned explanations on DT, an application for the optimization of individual charging processes is conceivable, in which, e.g., charging parameters are set depending on the SoH estimated by the DT to parameterize the charging process with regards to the charging duration or the increase in the service life of the ESS. With respect to charging strategies for heterogeneous fleets with different ESS, the charging strategy of the entire AGVS can be influenced by a DT in such a way that, as also shown in [33] and [34], an optimization of the transport execution time or the specific manufacturing costs can be achieved.

4.2.4 HOW TO INVESTIGATE IN EXPERIMENTAL ENVIRONMENT

As explained in section 4.2 above, charging processes for AGVs are not defined across systems. It is necessary to find out which system components have an influence on the charging process and how a unification could look like. A concept of such a unified charging process with the decentralized communication approach between AGV and CIS was presented in Figure 6. In the experimental environment, this unification of the charging process will be validated on a heterogeneous fleet.

Figure 5 provides a brief overview of possible communication concepts for the exchange of data relevant for the charging process. In a detailed investigation, the advantages and disadvantages of the different concepts will be determined with regard to their use in existing systems (retrofit), the expandability of systems (flexibility) and their applicability to heterogeneous fleets. The retrofitability and simplicity of the different communication concepts and implementation as well as expandability will be examined and evaluated at the experimental environment.

4.3 ADDITIONAL USE CASES

Additional use-cases can be implemented in the experimental environment, which are based on current research challenges in CPS and intralogistics:

- Fleet management systems (FMS) are the core of every AGVS. Implementing an FMS for the experimental environment will enable additional use-cases, like the investigation of different task allocation strategies.
- The shift from centralized to decentralized control systems introduces a use-case for the experimental environment to compare a centralized FMS to decentral task allocation and navigation. To compare both, metrics must be

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defined to investigate advantages and disadvantages of each approach.

- Using different navigation techniques allows different use cases of the AGVs. By implementing line-following, grid-based, SLAM-based navigation techniques and many more, the interaction of these in a heterogeneous system can be investigated.
- Physics-based simulations are effective tools in the continuous development process of intelligent robots and provide an accelerated and safe way to verify and test robotic algorithms. In the future, we aim to integrate a physics-based simulation for the CPIS to, e.g., test the limits of communication patterns in upscaled scenarios, which were not applicable in a real-world scenario. We further want to investigate how one can leverage physics-based simulations as a forecasting tool in the real-world scenarios.
- Known charging strategies for AGVS according to [27, 28] only consider systems consisting of homogeneous AGVs. Based on the previous consideration of homogeneous fleets, it can be assumed that the known charging strategies need to be extended to be applicable for heterogeneous fleets with different charging process requirements. For example, conditions for the allocation of CIS must be defined based on the technical parameters of CIS and AGV, which will increase the complexity of charging strategies depending on the number of different types of CIS and AGV. Finally, the knowledge gained so far shall influence the extension of a digital twin with respect to the charging processes.

5 CONCLUSION

The challenges in the automation of intralogistics and CPS are similar, since systems of heterogeneous, intelligent participants rely on communication and interoperability. To reach true scalability and changeability, a system must be modular, and a digital twin is needed to handle its communication. To cover this, the concept of cyber-physical intralogistics systems (CPIS) was introduced. A CPIS includes both physical and logical assets that have a digital twin in the virtual world. The structure and interface of the digital twins are defined on the descriptive layer. By having a standardized interface, the communication between all assets in the CPIS becomes possible. Prior unknown assets can be added to the system if they are following a definition from the descriptive layer and can be directly integrated in intralogistics processes.

The proposed CPIS is implemented in an experimental environment which includes a various number of model robots to create scenarios with different scales and complexities. Some possible use-cases were described in more detail to visualize, how this experimental environment will be utilized. By keeping the hardware complexity low, new algorithms can be implemented fast and the time for research cycles will be reduced. The environment can also be used in the context of lectures and courses and to introduce students to the concept of intralogistics and multi-robot systems.

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