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Autonomous Systems in Intralogistics – State of the Art and Future Research Challenges

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ABSTRACT

The paper at hand presents a definition of autonomous intralogistics systems and a classification of intralogistics systems with regard to their degree of autonomy. Intralogistics – a complex interplay of different logistics functions – covers the organization, control, execution and optimization of internal material and information flows. Over the past two decades, numerous authors have observed and proclaimed an increase in complexity in manufacturing and supply chain operations. A key approach to face this challenge is a paradigm shift from centralized, hierarchical organization structures towards, networked and autonomous systems. Autonomous intralogistics systems enable self-contained, decentralized planning, execution, control, and optimization of internal material and information flows through cooperation and interaction with other systems and with humans. Based on the definition of autonomous intralogistics systems, the authors propose a two-dimensional classification framework covering different automation stages for different intralogistics task levels. The developed classification framework is applied to various industry use cases to evaluate and discuss the state of the art regarding the implementation of autonomous intralogistics systems. Finally, the paper provides an outlook on future research and poses key research questions.

KEYWORDS: Logistics · intralogistics · autonomous systems · mobile robotics · decentralization · classification framework

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1. INTRODUCTION

1.1. Terminology, definition, and paper structure

In the course of digitalization, autonomously operating systems within intralogistics are increasingly gaining attention. Intralogistics – a complex interplay of different logistics functions – covers the organization, control, execution and optimization of internal material and information flows [1]. The term "internal" refers to selfcontained company sites, such as factories and warehouses or distribution centers, but also freight stations, freight terminals (e.g. combined road and rail terminals), inland ports, seaports and airports. Transport processes on public transport routes (road, rail, water, air), on the other hand, are not the subject of intralogistics. Figure 1 illustrates four exemplary intralogistics systems in a supply chain.

Over the past two decades, numerous authors have observed and proclaimed an increase in complexity in production, logistics and supply chain operations. Factors leading to the proclaimed increase include the globalization of business, dynamic and volatile markets, shorter product life cycles, increasing product variety and declining manufacturing depth [2, 3, 4]. An increase in complexity and in the dynamics of production and intralogistics systems are two major challenges for companies today. A key approach to facing these challenges is a paradigm shift from centralized, hierarchical organization principles and structures towards dynamic, networked, autonomous systems that cooperate with each other and are optimized in themselves in dynamically changing environments [5, 6, 7]. Scholz-Reiter and Freitag define the term "autonomy" as the independence of a system in making decisions by itself without external instructions, and performing actions by itself without external forces. As early examples, they mention autonomous production cells, automated guided vehicles, mobile autonomous robots, moving workstations, and dexterous robot grippers. These examples show that autonomy is not an absolute characteristic but relative to similar subsystems that act on the same hierarchical level within the entire system. That means the degree of autonomy of a subsystem is given by the freedom of action that is granted by the superior system-level and by the ability of the subsystem to use the given freedom of action [7]. Rammert distinguishes between three basic characteristics of autonomous systems [8]:

- autonomy over behavior,
- autonomy in decision making and
- autonomy in information processing/gathering

The autonomy of behavior enables a technical system to carry out various actions or series of actions in a fully self-contained manner. Autonomous decision-making refers to the ability to choose between possible courses of action. Autonomous information processing/gathering enables an autonomous system to gather and process information, which may lead to a subsequent change in behavior [9]. However, there is no common definition of autonomous intralogistics systems. Furthermore, there is a lack of clear classification to support the implementation and further development of autonomous systems in intralogistics.

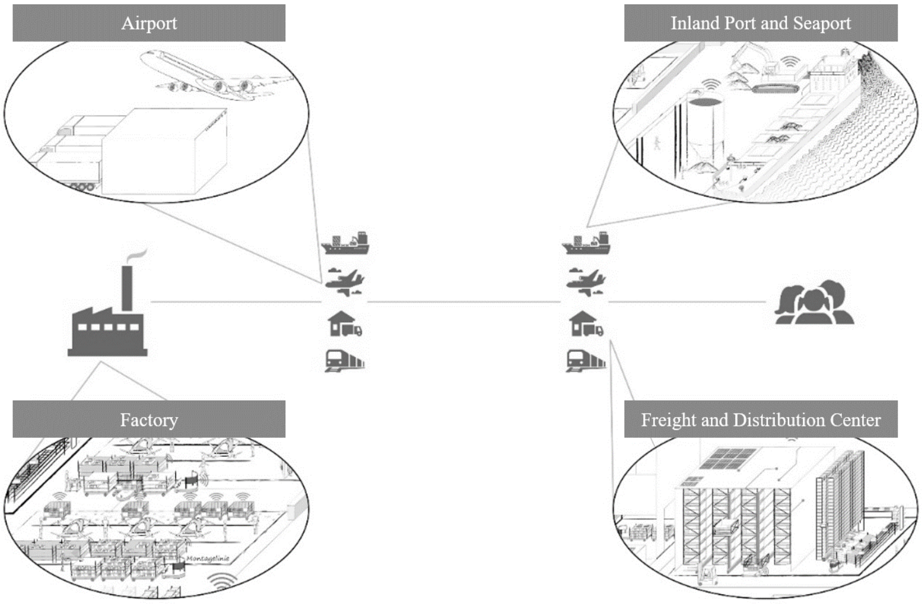

Figure 1: Examples of intralogistics systems

Due to this gap in research on autonomous systems, we propose the following definition for the concept of autonomous intralogistics systems: *Autonomous intralogistics systems enable self-contained, decentralized planning, execution, control, and optimization of internal material and information flows through cooperation and interaction with other systems and with humans.*

The ability to perceive information and to adapt their behavior according to changes in the environment allows autonomous intralogistics systems to operate even in highly complex and dynamic environments. Processaccompanying information flows as well as information for control and analysis represent a further essential component of autonomous intralogistics systems.

The following, we present a two dimensional classification matrix for autonomous intralogistics systems. This classification matrix serves as a guideline for the allocation of the stages of autonomy on the different task levels of an intralogistics system. In chapter 2, we provide an extensive review of the state of the art of enabling technologies and methods for autonomous intralogistics systems. The literature review forms the basis for the discussion of application examples of autonomous intralogistics systems in chapter 3. There, we apply the presented classification matrix to numerous industry application examples in order to validate the developed framework and to illustrate the autonomy stage of each application. Finally, we provide an outlook to current topics around autonomy in the context of autonomous intralogistics, and on future research challenges and questions in this area.

1.2. Classification matrix

Based on the presented definition, we propose a general classification framework for autonomous intralogistics systems. The framework consists of a matrix with two dimensions: the dimension of the task levels and the dimension of the automation stage. In the subsequent section, we take a closer look at both dimensions.

Task levels

The automation pyramid provides a general reference structure for task levels and related functions in industrial control and operations management (Figure 2) [10]. The lowest level (Level 0) represents the physical production and logistics processes. Within intralogistics, the following five basic process types can be distinguished: transport, storage, order picking, handling, and packaging. Transport is the movement of goods from a source to a sink. In storage, materials are stocked or buffered for later use [11]. Order picking is the retrieval of certain items from stock based on specific requirements to fulfill customer orders [12]. Handling describes the physical manipulation and placement of goods. To prepare and protect the materials for shipping, it passes through the packaging process [13]. The next level in the pyramid (Level 1) represents the level of sensors and actuators embedded into the technical systems that execute the physical processes. Tasks and functions at Level 1 include the collection of sensor data, actuator control and I/O control. Level 1 is followed by the process control level (Level 2) which receives the information from the device level, such as the current status or position of shop-floor devices and coordinates all activities on this process level. Examples of tasks or functions

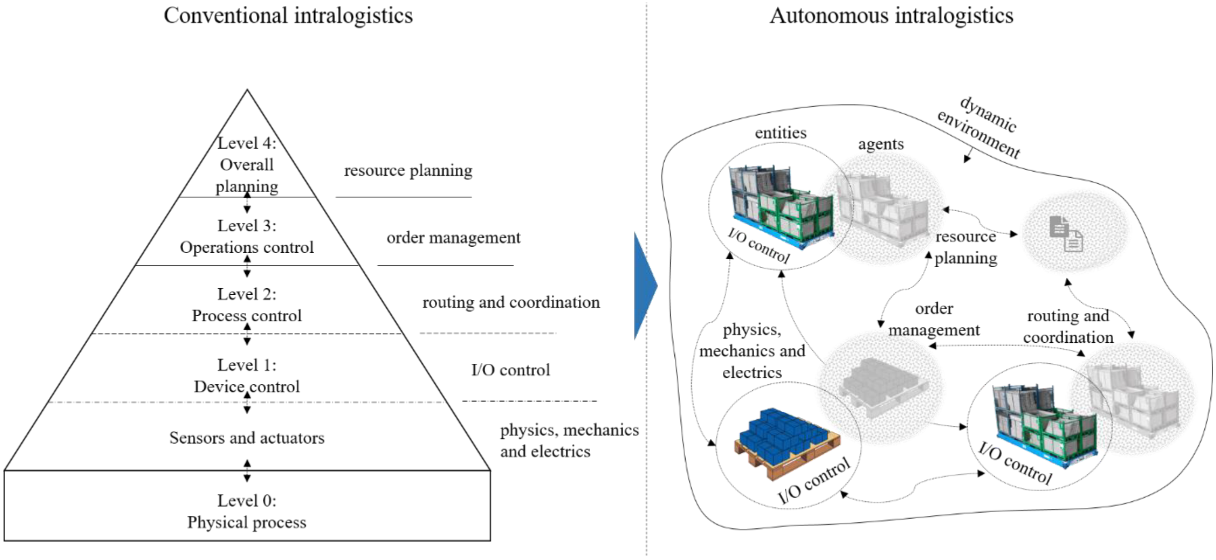

Figure 2: Paradigm shift from hierarchical, centralized intralogistics systems (conventional intralogistics) towards autonomous intralogistics systems

at Level 2 are object routing or coordinating tasks. Level 3 contains all functions for operations control and short-term planning, such as order or inventory management. The top-level (Level 4) focuses on mid- to long-term planning activities, such as resource planning [14]. With the proclaimed paradigm shift from a hierarchical, centralized control of intralogistics systems to decentralized autonomous control, existing barriers between the different hierarchy levels are increasingly being dissolved. Autonomous entities and agents cooperate to solve complex control and planning tasks, leading to a local fusion of levels and functions (Figure 2) [10, 15]. However, the distinction between the different types of tasks of industrial automation from physical control to overall system planning (Level 0-5) still applies.

Automation stages

When considering steps towards autonomous intralogistics systems, it is useful to look at the developments in autonomous driving in public transport. As early as 2014, the SAE J3016 standard described the classification and definition of terms for road-bound motor vehicles with autonomous driving systems, published by SAE International (formerly: Society of Automotive Engineers). The classification lists six degrees of autonomy (0 to 5) and describes their minimum requirements [16]. A comparable stage model for intralogistics, however, needs to consider not only the physical level of the „vehicle", but also higher-level monitoring, control, and planning tasks as described in the previous section. Therefore, in Figure 3 we propose five automation stages, which are adopted for autonomous intralogistics systems. The following four key aspects illustrate the differences between the stages: environment, decision making, interaction and self-optimization. These aspects are based partly on the ALFUS (Autonomy Levels for Unmanned Systems) [17] and the LORA (Levels of Robot Autonomy) framework [18].

The first characteristic of Stage 5 (Autonomy) is a highly complex and dynamic environment, e.g. intralogistics systems can handle rapidly changing structures with multiple traffic. In alignment with the definition presented in chapter 1.1, decision making is decentralized in Stage 5, i.e. autonomous systems can decide for themselves in various situations, and at the same time communicate with other systems. This leads to the third characteristic of Stage 5, the high interaction between independent systems. The capability of learning and self-optimization, which includes – according to Bloom's Taxonomy [19] – the ability to remember, to understand, to apply, to analyze, to evaluate and to create, is the last key aspect of autonomy [20, 21]. Besides these four aspects, the overall responsibility is fully assumed by the system. In contrast to this, Stage 0 (No Automation) can be characterized by manual decision-making and no system interaction. However, a manually operated industrial truck, for instance, can act in both static and dynamic environments. This can be derived from the presence of a human operator, who takes over complete responsibility and can adapt to dynamic changes in the environment.

Based on the two introduced dimensions, we propose a general classification matrix for autonomous intralogistics systems displayed in Table 1. It should be noted that each task level can achieve a different automation stage.

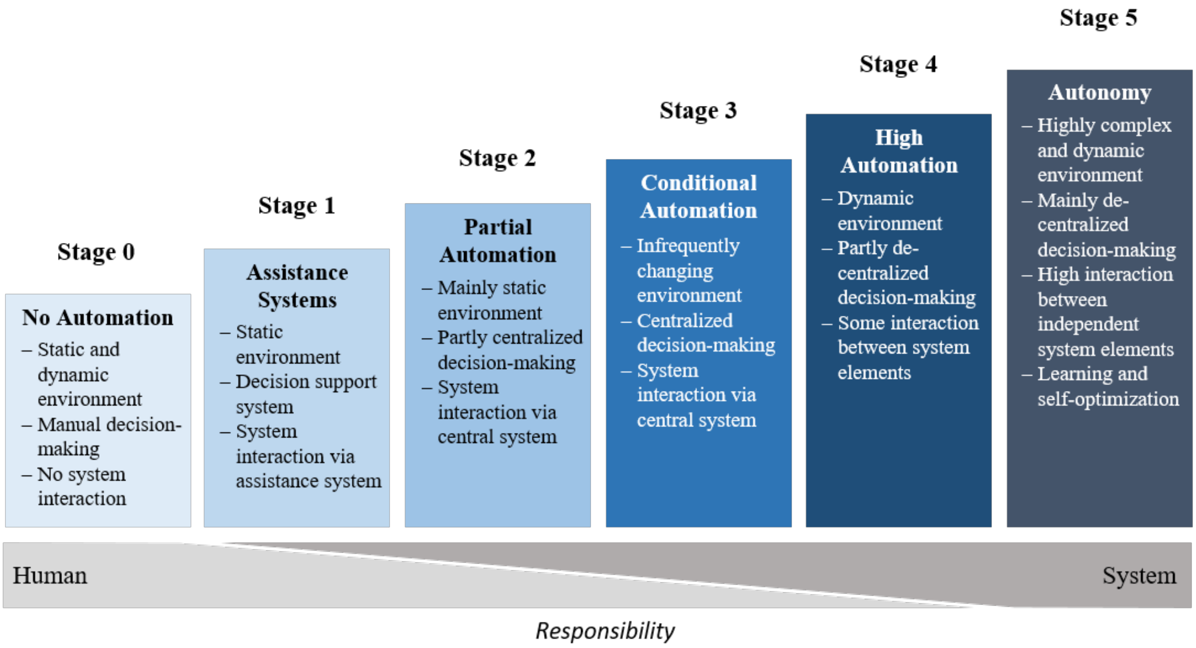

Figure 3: Automation stages towards autonomous intralogistics systems

Table 1: General classification matrix for autonomous intralogistics systems

Task level	Automation stages Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Overall system planning (Level 4)	Manual decision making in overall system planning	Decision support system in overall system planning	Partly centralized decision making in overall system planning	Centralized decision making in overall system planning	Partly decentralized decision making in overall system planning	Decentralized decision making in overall system planning
Overall system control (Level 3)	Manual decision making in overall system control	Decision support system in overall system control	Partly centralized decision making in overall system control	Centralized decision making in overall system control	Partly decentralized decision making in overall system control	Decentralized decision making in overall system control
Process control and monitoring (Level 2)	Manual decision making in process control and monitoring	Decision support system in process control and monitoring	Partly centralized decision making in process control and monitoring	Centralized decision making in process control and monitoring	Partly decentralized decision making in process control and monitoring	Decentralized decision making in process control and monitoring
Device control and information processing (Level 1)	Manual search and transfer of information on demand	Assisted search and transfer of information on demand	Assisted and partly self-contained information acquisition and processing	Fully self-contained information acquisition, generation of information and interaction with central system	Fully self-contained information acquisition, generation of information and partly interaction with other system elements	Fully self-contained information acquisition, generation of information and interaction with other system elements
System execution and real time control (Level 0 and 1)	Manual execution in static environment	Manual assisted execution in static environment	Assisted and partly self-contained execution in static environment	Partly self-contained execution in infrequently changing environment	Fully self-contained execution in dynamic environment	Fully self-contained execution in complex and dynamic environment

Figure 4 shows an example of an automated-guided vehicle system (AGVS). The individual vehicles (Level 0/1) may be able to navigate freely around obstacles (Stage 4), but they receive their transport orders from central IT systems (Stage 2, Levels 2 and 3) [22]. On the other hand, a certain planning autonomy can be implemented at the system control level (Stage 3, Levels 3 and 4), e.g. by a multi-agent system.

The blue line in Figure 4 shows symbolically the automation stage of an AGVS at the different task levels of an intralogistics system. In addition, the matrix design allows several systems to be shown and compared. The line therefore does not illustrate a mathematical relationship, but simply illustrates the degree of autonomy of the entire system at hand.

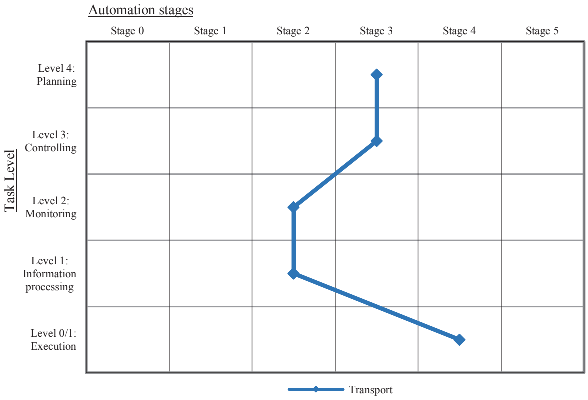

Figure 4: Example of the classification matrix based on an automated-guided vehicle system

2. TECHNOLOGIES AND METHODS

2.1. Basic technologies

In this chapter, we outline the current state of technologies that enable the autonomy of intralogistics systems. Autonomous systems must have the ability to perceive environmental conditions, to process information, to identify other systems or objects and to communicate with the environment [7]. In this context, Lee introduced the term "cyber-physical systems" (CPS) to describe the ongoing integration of physical processes with virtual processes and computation [23]. Cyber-physical systems contain embedded processors, sensors and actuators, which provide them with access to global networks and to humans using communication interfaces [24, 25]. Other authors use the term "smart objects" [26, 27, 28] or the "internet of things" (IoT) [29, 30] to describe physical objects capable of sensing, data processing and network-based communication. For an overview of the terminology of CPS and related concepts, we refer to [31].

According to the aforementioned concepts and technologies, we define the following basic technology components for autonomous intralogistics systems: 1) sensors, 2) actuators, 3) machine-to-machine (M2M) communication, 4) human-machine interaction (HMI) and 5) computation hardware.

2.1.1. Sensors

Sensors allow autonomous systems to perceive their environment, and to capture and to compute relevant data. Tränkler defines sensors as technical systems that acquire input values (physical, chemical or biological measures) and return certain preprocessed output values [32]. Sensors can fulfill various functions such as *identification, localization, safety or condition monitoring* [33, 34].

As previously mentioned, one important ability of autonomous intralogistics systems is *identification*. The DIN 6763 norm defines identification as the clear and unambiguous recognition of objects based on specific characteristics with defined accuracy [35]. Identification characteristics can include an object's width, length, weight or material. Besides an object's characteristics, a unique identification number can be used for identification purposes [34]. **Optical** sensors allow autonomous intralogistics systems to identify objects based on specific optical characteristics, or based on labels attached to the objects. The identification information can be provided on the labels in plain text or code (1D/2D codes). 1D codes can be read by laser scanners [36]. For identification with 2D codes or object specific characteristics, camera sensors and image processing methods are required [37, 38]. Depth information regarding objects can be provided by stereo cameras [39, 40], structured light [41] or timeof-flight (ToF) sensors [42, 43], which produce 3D point clouds of objects (Figure 5). Image-processing algorithms allow autonomous systems to process the recorded and transformed point clouds and to detect object-specific patterns, surfaces or contours for identification [44]. These computer or machine vision approaches enable autonomous intralogistics systems to identify goods [43, 45], pallets [42, 46, 47] or other objects, and to semantically understand their working environment (Figure 6). Besides optical identification, also **radio frequency-based** technologies such as Radio Frequency Identification (RFID) and Near Field Communication (NFC) are used in autonomous intralogistics systems for the purpose of contactless identification without direct line of sight [48]. Radio frequency-based identification systems consist of transponders, sender/reader units and processing units. Transponders contain the identification information and are attached to the identification objects [49, 50] or load carriers that are assigned to an object [51, 52]. Depending on the application case, different types of transponders with varying frequencies, storage sizes, reading ranges or energy supplies can be selected [53, 54, 55].

Besides identification, sensors are used for *localization* in industrial environments [7]. Localization is the determination of an object's physical position in a defined coordinate system [57]. The physical position is described by the exact coordinates and orientation, also referred to as "pose" [58]. Localization forms the basis for navigation and movement in a given space. Generally, one can distinguish between position bearing (e.g. triangulation, simultaneous localization and mapping (SLAM) etc.) and position-coupling approaches (odometry, dead reckoning etc.) [59]. Position bearing estimates the relative position of an object to markers, natural landmarks or transponders. Markers can be installed in lines, point sequences or grids on floors, walls or ceilings [60, 61]. Within **marker-based** localization, one can distinguish between inductive, magnetic or optical sensor technologies [59, 62]. Besides artificial markers, natural landmarks can also be used for localization. Technologies for position bearing based on **natural landmarks** include ultrasonic range-finding as well as camera or laser sensors, often referred as optical radar or LiDAR (light detection and ranging) [63, 64, 65]. These types of sensors are used for SLAM approaches where autonomous systems have to navigate in unknown environments without existing maps or localization information [66, 67, 68]. In these scenarios, autonomous systems use camera or LiDAR sensors to create a map of their

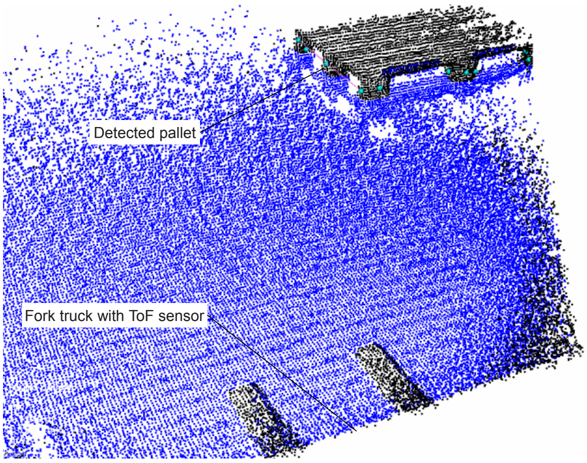

Figure 5: Pallet detection with 3D camera technology [47]

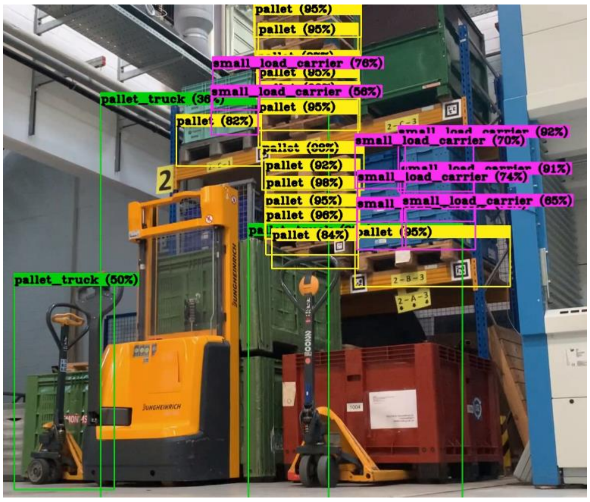

Figure 6: Optical identification of logistics specific objects in industrial environments [56]

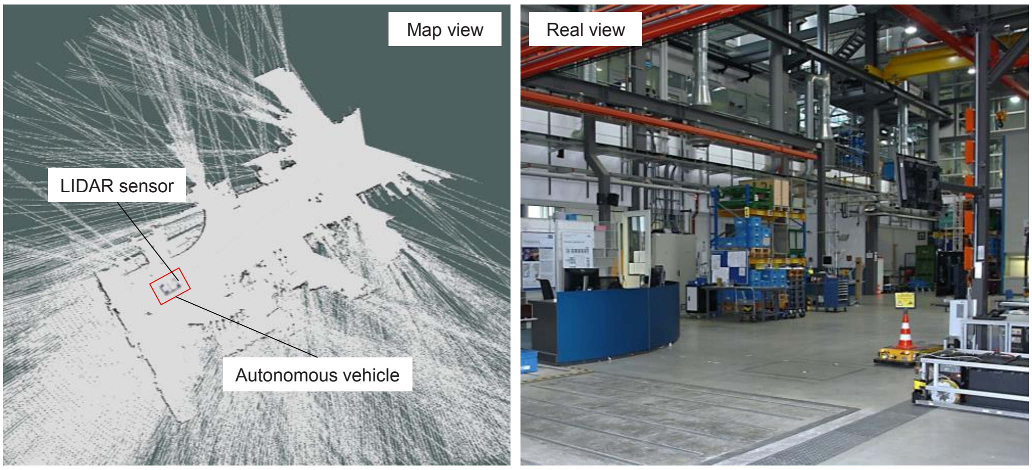

Figure 7: Autonomous map-building of mobile robots using LiDAR

environment, while moving (Figure 7). Starting from an initial point the autonomous system continuously maps the environment while localizing itself relatively to the created maps based on detected landmarks [68]. Cadena et al. [69] provide an overview of relevant SLAM problems and approaches. Besides marker- and landmark-based approaches, autonomous systems also use active transponders for localization. Examples for position-bearing technologies with active transponders in outdoor environments are global navigation satellite systems (GNSS) such as the Global Positioning System (GPS) or other **radio-based** technologies such as Low Power Wide Area Network (LPWAN), Long Range Wide Area Network (LoRaWAN) or Narrowband-IoT (NB-IoT) (Table 2) [70, 71]. Examples of radio-based technologies for indoor environments are Bluetooth and Ultra-wideband (UWB) [72]. Position coupling computes an object's position by integrating internally measured parameters of motion and direction such as wheel rotation, speed and acceleration. Relevant parameters are measured via **internal** measurement units (IMU) [73] such as rotatory sensors (odometers, accelerometers etc.) and translational sensors (inertial angular acceleration meters, incremental encoders etc.) [58]. For more detailed evaluations and technology comparisons, we refer to the following studies [74]. Mautz notes that the combination or fusion of data from different sensors can be used to further enhance localization performance [75]. Durrant-Whyte and Henderson discuss different multisensory data fusion techniques, including grid-based models, Kalman filtering and sequential Monte Carlo methods [76].

Besides identification and localization, sensors are used to ensure operational *safety*. According to DIN EN ISO 12100 autonomous intralogistics systems can be classified as machines and therefore have to comply with norms and standards regarding safety aspects of machinery [77]. The term "safety" includes reliable compliance of technical functions as well as risk-minimization measures with respect to humans and the environment in general [78]. To ensure safety, autonomous systems are equipped with safety technology. Sensors belong to the category of sensitive protection devices. Sensitive protection devices detect humans or objects within a certain range of an autonomous system and send signals to corresponding control systems [79, 80]. Examples of sensitive protection devices are **tactile** sensors and bumpers, **capacitive** sensors, **ultrasonic** sensors and **optical** sensors (light barriers, infrared, cameras or laser scanners) [81, 82]. In contrast to other sensors, cameras can distinguish between humans and other objects using computer vision methods [83, 84, 85]. Shi et al. use camera and computer vision-based face recognition to detect humans and to plan optimal trajectories for mobile robots [86]. Zhang et al. present an approach for

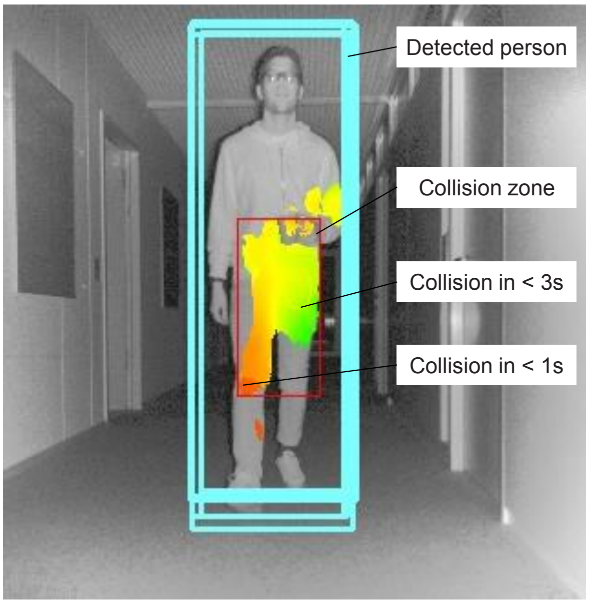

Figure 8: Detection of humans and collision warning using computer vision [85]

multiple human detection using a color-depth camera mounted on a mobile robot platform [87]. The ability to detect humans allows autonomous systems to adjust their movements and to prevent collisions. In Figure 8, the time-of-flight camera sensor detects a potential collision between the system and a person in less than a second. The system was trained using machine-learning algorithms to distinguish people from non-human objects, enabling more sensitive reactions and warnings depending on the situation [88].

Finally, sensors are applied to monitor the *condition* of autonomous intralogistics systems and their environment. Examples of this are sensors to measure **load, torque, vibration, temperature** or **energy** consumption [89, 90, 91]. Wenzel and Bandow state that the acquired condition data can be used to enhance maintenance efficiency in intralogistics systems through predictive analysis [71, 92].

2.1.2. Actuators

Another basic technology are actuators that allow autonomous intralogistics systems to move in dynamic environments and to physically influence their environment, for example by executing handling operations. Common technologies are **electric** drives, including rotating and linear electrical machines, magnetic bearings and tension magnets [93, 94]. Besides electric drives, **fluid** technologies such as pneumatic or hydraulic actuators are commonly used, especially for hoists or lift operations [95, 96, 97]. Material flow in an intralogistics system is established by linking machining, processing and goods distribution [98, 99]. Material flow is an interplay of different types of conveyor systems, discontinuous and continuous systems, with different types of actuators [100]. Figure 9 displays a conveyor system based on small-scale, cyber-physical transport modules which allow for the multi-directional movement of goods. The control of the modules and drives is decentralized, which means that the modules exchange information and cooperate to solve the transportation task [101, 102, 103, 104]. One major challenge for autonomous intralogistics systems regarding actuator technology is the picking, gripping or manipulating of goods. High **mechanical** and cognitive demands are placed on gripping technologies, which can grip and hold the goods securely by means of a combination of force and form closure [105]. Systems have to react flexibly to different goods characteristics and positions [106, 107]. Figure 10 shows a nature-inspired octopus gripping technology, which is used for the automated unloading of goods out of containers. Another challenge for autonomous intralogistics system is the energy supply required to complete the assigned task. This can be done via an active power supply for example via combustion engine, electric motor with battery and electric motor without battery [108]. Alternative energy-supply solutions include passive or inductive technologies [59, 62] up to autarkic self-supply via methods of energy harvesting [109].

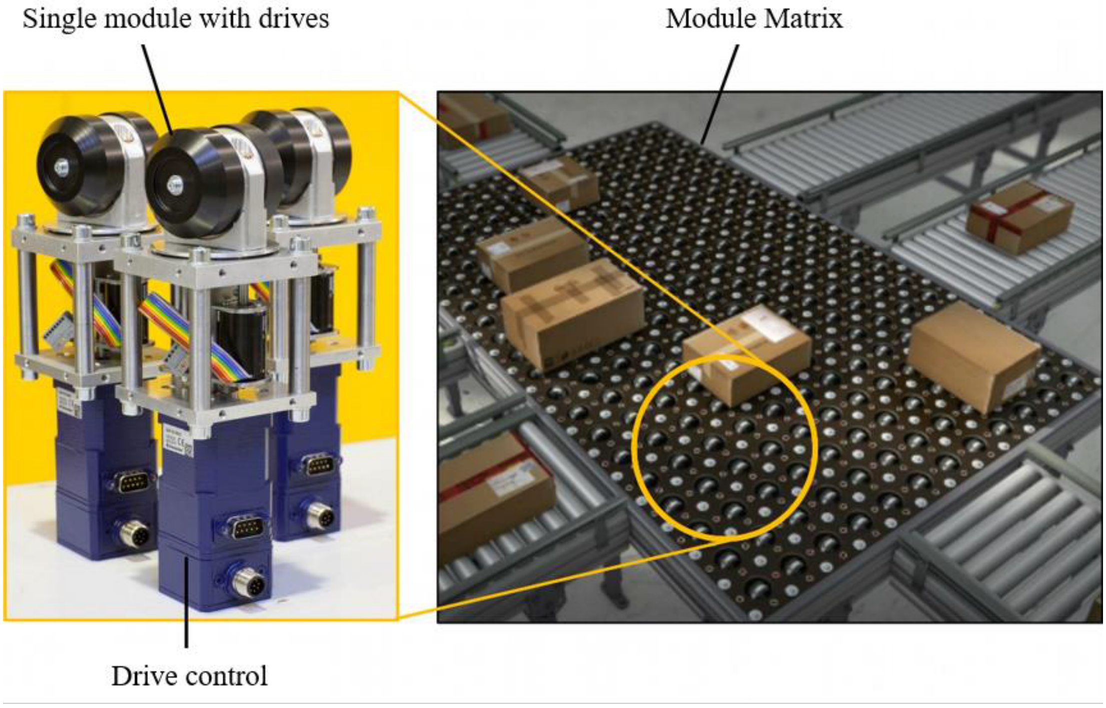

Figure 9: Decentralized, distributed control of large-area conveyor systems [110]

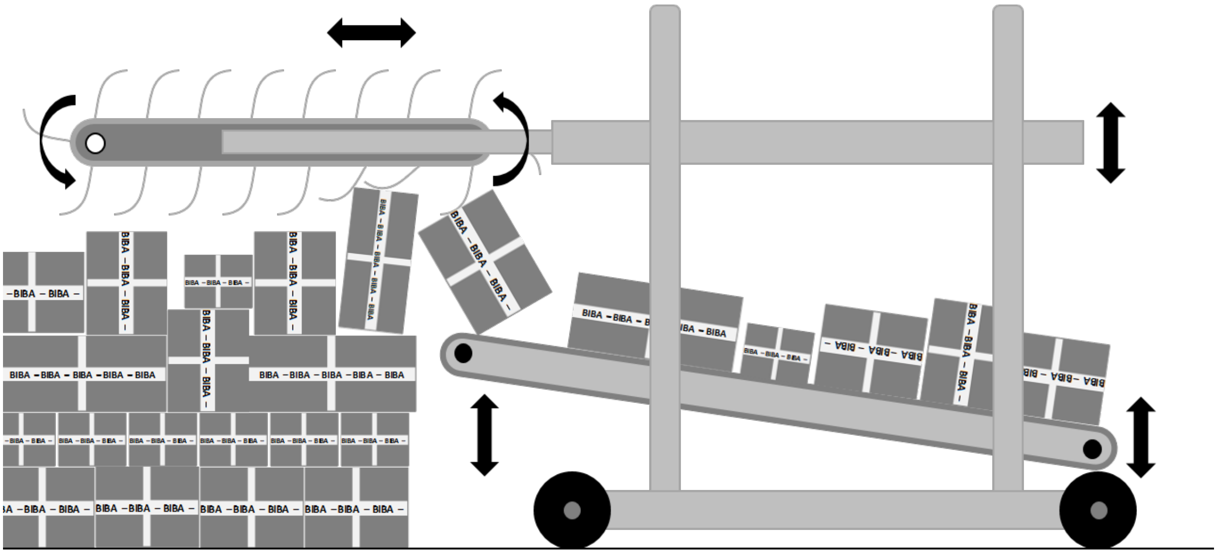

Figure 10: A bionic octopus gripper for unloading heterogeneous parcels out of containers [111]

2.1.3. Machine-to-machine (M2M) communication

According to the DIN standard 43863-4 machine-to-machine (M2M) communication is described as automatic technical communication processes between machines using a communication network of choice [112]. To facilitate the communication processes between machines, certain standards and rules are required. One example is the ISO/OSI reference model, which provides a basis for the standardized communication between two machines over several abstraction layers. From a technological standpoint, machines can communicate via wired and wireless technologies (Table 2) [34, 113, 114]. At the field and cell level, usually wired **fieldbus** systems are used. Bus systems connect sensors and actuators to their corresponding control and computing units. Examples of open fieldbus standards are PROFIBUS and CAN [115]. In addition, technologies from the **industrial ethernet** sector such as Ethernet/IP or EtherCAT are increasingly applied [116]. Examples of **radio-based** communication technologies are wireless local area network (WLAN), Bluetooth, LPWAN, LoRaWAN, NB-IoT and cellular networks [117, 118, 119]. Wireless technologies have the advantage of avoiding time-consuming and costly wiring [120] as well as enabling mobile objects to communicate directly with each other. Figure 11 shows a prototype of a smart and connected special load carrier. The load carrier is equipped with wireless LoRaWAN communication technology. The sensors and communication interfaces allow the load carrier to communicate with other systems and to exchange data over a higher-level cloud platform [121]. However, the advantages of wireless technologies often stand in conflict with the required high transfer speeds and real-time capabilities demanded for automation [103].

Figure 11: Smart and modular special load carrier for a cloud-based service system using LoRaWAN [121]

2.1.4. Human-machine interaction (HMI)

The communication and interaction between humans and machines are an important aspect for the successful implementation of autonomous intralogistics systems. A **vision-based** method of interaction between humans and machines is the provision of information using Augmented Reality (AR). The term generally refers to the computer-aided expansion of the perception of reality. In this process, virtual, computer-generated information is transmitted to humans via visual projections in the real-world environment [122, 123, 124]. The visualization medium constitutes the user interface. The corresponding information can be projected onto head-mounted displays, glasses or handheld devices. Examples include procedures with mobile data terminals, AR in maintenance [125], layout

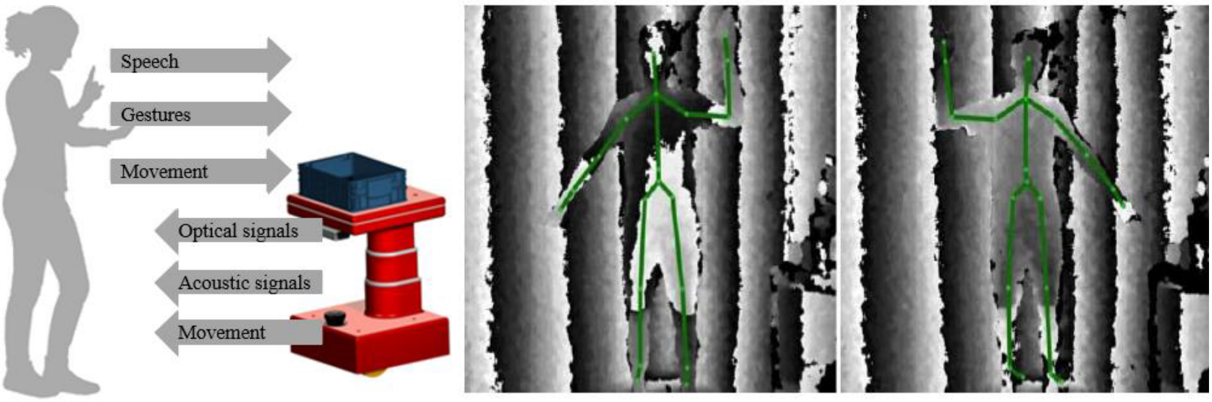

Figure 12: Gesture controlled transportation robot "FiFi" [131]

planning and optimization systems [126] or Pick-by-Vision systems [127, 128]. Another form of human-machine interaction is **voice** control. This type of communication is easy to learn and allows intuitive communication between humans and machines. Studies show that voice control functions in a manner independent of the speaker. Alertness, attention and/or interference signals, however, can have a significant influence on the communication performance [129, 130]. A third principle for the interaction between humans and autonomous systems is **gesture**-based communication (Figure 12), whereby autonomous systems use optical sensors to recognize humans and gestures based on 3D data. Operators can assign tasks to a particular system with specifically programmed gesture commands, while the machine uses **optical** and **acoustic** signals to communicate with the operator [131, 132]. One challenge here is to minimize false detections [133].

2.1.5. Computation hardware

Sensors and actuators are connected with each other via the processing of information [100, 134]. The information processing is executed by the computation hardware embedded into an autonomous system. Examples of **computation** technologies are Programmable Logic Controllers (PLC), microcontrollers and industrial PCs [135]. According to IEC 61131, PLCs can be organized into networked, hierarchical structures, and represent the most important controllers in material flow-technology [136, 137]. Industrial PCs are used for higher-level control tasks and multi-sensor data processing [138]. Free programmable microcontrollers offer a variety of functions, especially for simple control tasks. However, studies show that microcontrollers can also execute more demanding navigation tasks, including obstacle avoidance [139], and even complex algorithms from the field of artificial intelligence such as neural networks [140] and rapidly random exploring trees (RRT) [141].

Table 2: Basic technologies for autonomous intralogistics systems

1) Sensors	**Category**	**Examples**
Identification	Optical	1D/2D code, camera
	Radio-based	RFID, NFC
Localization	Marker-based	Inductive, magnetic or optical sensors
	Natural landmarks	Ultrasonic, camera or laser sensors
	Radio-based	GPS, cellular, WLAN, Bluetooth, UWB, RFID, LPWAN
	Internal	Odometer, accelerometer, inertial sensors, incremental encoders
Safety	Tactile	Touch sensors, bumpers
	Optical	Light barriers, infrared, laser, camera
	Others	Induction loops, capacitive sensors
Condition	Condition sensors	Load, force, torque, vibration, energy consumption sensors

2) Actuators		
Motion & handling	Electric drives	Rotating/linear electrical machines, synchronous machine, magnetic bearings, tension magnets, linear motors
	Fluid technology	Pneumatics, hydraulics, vacuum technology
	Mechanical	Mechanical manipulators
3) + 4) Communication		
Machine-Machine	Fieldbus	PROFIBUS, CAN, ASI, InterBus-S
	Industrial ethernet	Profinet, Ethernet/IP, EtherCAT, Powerlink
	Radio-based	Bluetooth, WLAN, ZigBee, SigFox, LPWAN, LoRaWAN, NB-IoT, cellular
Human-Machine	Vision/optical	Smart glasses, displays, projectors, lights
	Voice/acoustic	Speakers, microphones
	Gesture	Camera
5) Computation hardware		
Information processing	Computation	PLC, microcontrollers, industrial PCs

2.2. Methods for Planning, Controlling and Optimization

2.2.1. Introduction

Having introduced the basic concepts of automation and autonomy and the basic enabling technologies, this section describes methods for planning and controlling autonomous systems within the basic functions of intralogistics.

As described in chapter 1, the application of autonomy leads to independent decision-making of a system or even multiple independent decision-makers in a system (analogous to the paradigm of multi-agent systems). The underlying idea is that the sum of multiple single decisions will lead to a beneficial overall system behavior. However, with increasing autonomy and especially with an increasing number of independent decision-makers, it becomes more and more difficult to predict the exact system behavior. Even though problems in intralogistics systems could often still be solved by hierarchical, centralized approaches, this does collide with the idea (and the advantages) of autonomous entities. The ability of the autonomous system entities to make their own independent decisions is restricted when combined with centralized approaches. According to Klein "decentrality" is based on a distributed implementation (multiple decision units) and decisions are made based on local information only [142]. However, in practice the information constraint is usually less strict, as autonomous entities are often able to communicate and exchange information. Furthermore, the threshold between centralized and decentralized approaches is not strict. It is possible to combine characteristics of

Basic functions of intralogistics

Transport	Storage	Picking Packaging Handling
Vehicle systems • System design • Task assignment • Empty vehicle management • Routing • Deadlock avoidance Conveyor systems • Routing • Deadlock avoidance	• Assignment • Zoning • Allocation	• Identification of item • Control of grabbing • Movement • Bin/ pallet/ container packing problem

Figure 13: Subproblems for basic functions of intralogistics

both paradigms within a single system, such that, for example, central status monitoring (global information) can exist, with multiple entities autonomously deciding on this information. Seibold and Furmans describe the general advantages of decentralized approaches [143]. Schmidt et al. categorize approaches based on decentralized control in the area of multiple-vehicle transport systems [144].

When it comes to the planning and control of autonomous systems, discrete event simulation is most often used for support – in particular to cope with increasing complexity [145]. Nonetheless, agent-based modeling (in simulation) can also be applied, especially in modeling the interaction of multiple autonomous entities. However, results of a simulation cannot be generalized, as the results are valid for the exact simulated scenario only. Therefore, simulation can only be a part of a planning process, e.g. to evaluate a concept. Regarding the controlling of an autonomous system, a simulation can help to develop, evaluate and compare different control methods. In this context, the simulation supports the system designer with dealing with the complexity of various methods for controlling, but is no method of control itself. In applications including a digital twin, a simulation can however be used to provide a forecast. Hence, the real-world application can be controlled based on the results of the simulation.

The following section presents specific methods for planning, controlling and optimizing autonomous systems applied in the basic fields of intralogistics systems. Figure 13 shows a summary of the subproblems dealt with in the following subsections.

2.2.2. Transport

Regarding the transport systems, we first deal with intralogistics vehicle systems followed by conveyor systems in the second part.

In order to run an autonomous intralogistics vehicle transportation system, the following problems need to be addressed [144] (Figure 14):

- System design: How many vehicles are necessary? This task can be seen as a Level 4 process (Figure 2).
- Task assignment (dependent on the look-ahead period and information used also known as "dispatching" or "scheduling"): Which (transportation) task is done by which vehicle? This task can be seen as a Level 3 process (Figure 2).
- Empty vehicle management (also "vehicle positioning"): How do vehicles without current task behave? This task can be seen as a Level 3 process (Figure 2).
- Routing: How to reach a destination in a given layout? This task can be seen as a Level 2 process (Figure 2).
- Deadlock avoidance and deadlock resolution. This task can be seen as a Level 2 process (Figure 2).

The described subproblems cannot be regarded separated from each other, as there are strong interdependencies. For example, the travel time, which is the result of a given routing strategy, can be a major criterion for task assignment. However, the routing strategy can only be executed based on a certain task assignment. The mentioned interdependencies are responsible for the high degree of complexity using autonomous units in intralogistics systems. The used method and the available computational time can therefore have a strong impact on the performance of a multi-vehicle system. When using a fleet of autonomous vehicles, each vehicle makes its own decision – usually based on incomplete (e.g. local) information – on the next task to perform or the precise route to take.

The **system design** for a vehicle transport system can be regarded as a very complex planning process, since all other variables and factors need to be taken into consideration. Han et al. stated that "determining the optimal numbers of vehicles is the fundamental problem in the management of an AGV [automated guided vehicle] system" [146]. Some authors propose analytical approaches (e.g. [147, 148]); however in recent years the vast majority of publications have relied on simulation approaches. Vivaldini et al. propose an iterative procedure of simulation on the one hand, and the adjustment of the input parameters on the other, in order to determine the number of vehicles in a system with respect to vehicle-routing and task assignment strategies [149]. Chang et al. use multiple simulation runs to generally determine correlations between certain design parameters, e.g. the number of vehicles and layout characteristics [150].

There exists a vast body of literature regarding systematic approaches for **task assignment**, where a number of (transportation) tasks need to be distributed over a fleet of vehicles. The approaches range from rather simple dispatching rules, which only take the current system status into account, to complex scheduling approaches, including a planning aspect, which also take future tasks into consideration [151, 152, 153]. However, most publications discuss approaches with a central decision unit based on complete, global accessible information. As already explained in Section 2.2.1, systems with multiple autonomous units tend to use decentralized approaches instead. Schmidt et al. distinguish two major categories of the decentralized approach to task assignment: layout simplifications to enforce a decentralized approach, and multi-agent systems [144]. In terms of the number of publications, the main focus is on the latter. Klein develops multiple approaches with the main focus of using local information only, and compares his decentralized approaches with a centrally structured benchmark approach [142]. Fanti et al. published a decentralized approach, whereby multiple autonomous vehicles are able to communicate within a certain radius to negotiate and distribute open tasks [154]. Many publications in the area of decentralized task assignment rely on auction-based methods for the

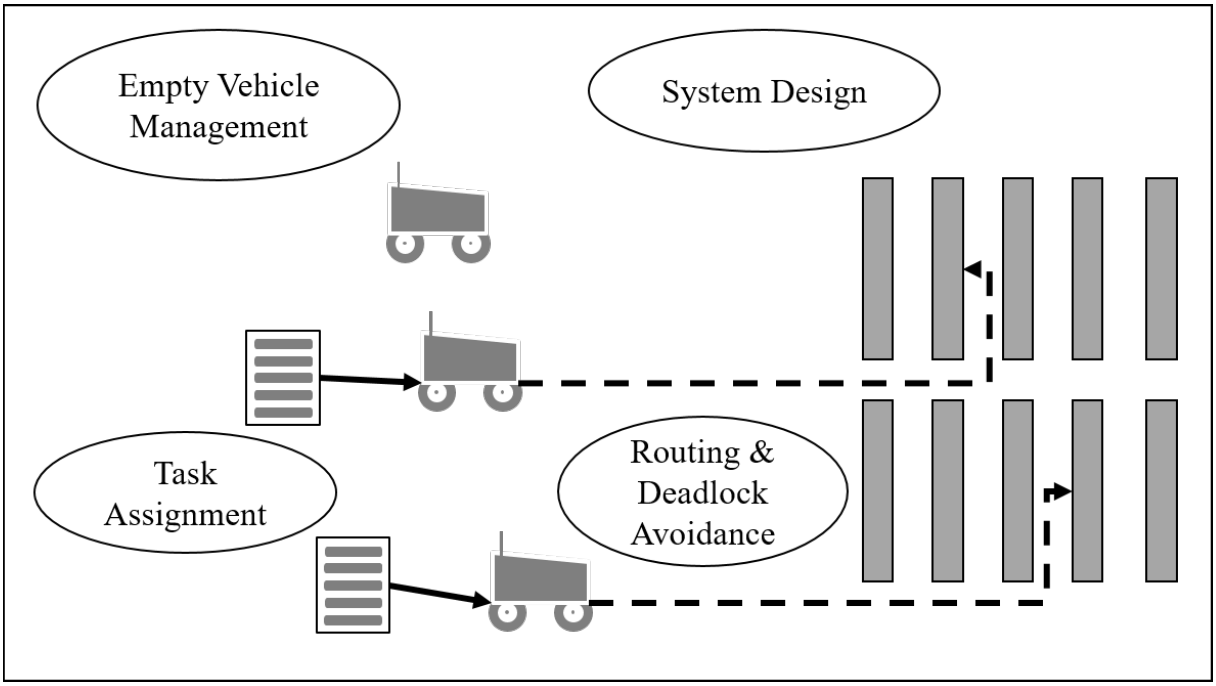

Figure 14: Main decision problems within intralogistics vehicle transportation systems

assignment, based on the so-called CNET-protocol [155] and its enhancements. Generally speaking, in auction-based approaches the autonomous vehicles compete against each other for open tasks via offers they make, or (vice versa) the tasks compete for the vehicles via offers. The vehicle or job with the best offer obtains the approval. Schwarz et al. use an enhancement of the CNET-protocol as an auction-based approach, where a single vehicle is able to compete in multiple auctions at once [156]. Martín et al. describe an approach where tasks are awarded to multiple vehicles at once, which leads in particular to high system robustness [157]. Giordani et al. present a two-level bidding algorithm, which firstly calculates the number of necessary vehicles and secondly assigns the tasks to specific vehicles [158]. Results show that the decentralized task assignment causes higher costs, but is more robust compared to a centralized benchmark strategy. Furmans et al. describe a system called KARIS, which consists of a fleet of multiple autonomous vehicles equipped with a conveyor [159]. The vehicles are able either to form a conveyor that can adjust itself to a changing environment, or to perform combined transports of heavy weights. Therefore, this system can be seen as a combination between a vehicle-based system and a conveyor. The vehicles use an auction-based approach to task assignment. Weyns and Holvoet propose a field-based method [160]. Open transportation tasks emit an attracting field, whereas vehicles repulse themselves. When calculating the resulting field at each spot of the layout, each vehicle merely has to follow the gradient. Another field of decentralized strategies for task assignment allows vehicles to communicate with each other within a certain area and exchange previously assigned tasks [160, 161, 162].

Empty-vehicle management can be seen as a problem related to task assignment. From a vehicle's perspective, a trip to a certain parking spot is similar to a new task. Le-Anh divides approaches into four different categories, whereas in our opinion only the "distributed positioning rule" is non-trivial from a controlling point of view [151]. A popular approach consists of monitoring the number of vehicles within a certain area and comparing them to a predefined minimum number of necessary vehicles, sometimes referred to as "watermark" (see e.g. [163, 164]).

Schmaler et al. include forecast information for management of empty vehicles. However, all mentioned approaches for the vehicle positioning are somehow centrally implemented. Therefore, these approaches restrict the autonomous decision making of a vehicle [165].

The **routing** problem consists on the one hand of the calculation of a specific route from a start location to a destination and, on the other, of the gradual execution of multiple single path segments. The optimization goal of the routing is dependent on the perspective with regard to the problem: Using a centralized perspective of the entire system and fleet, the objective function may be to minimize the sum of transportation times or to maximize the overall vehicle throughput. However, with a decentralized perspective for a single vehicle, the objective may be the minimization of the individual driving time, with or without a consideration of the consequences of the ego vehicle's movement on the rest of the fleet. The problems of **deadlock avoidance** and **deadlock resolution** are strongly linked to the routing problem. Therefore, both problem types are often regarded together. Furthermore, the layout (size, complexity, uni- or bidirectional paths) has a high impact on the routing. Some vehicle systems do not use any physical paths at all – the vehicles follow trajectories in space. Approaches which focus on a planning process of a routing solution are only practicable in comparably small environments with a low number of vehicles [166]. Due to the high complexity and uncertainty of driving times, the controlling aspect is more important in routing. Schmidt et al. categorize the decentralized routing approaches in swarm-based approaches, analogies to ad-hoc networks and multi-agent systems [144]. Most of the publications in that field are somehow related to multi-agent systems. Klein develops a completely decentralized routing strategy, where autonomous vehicles strictly use local information only and, therefore, the vehicles do not even have any information about the current system status or the general layout [142]. As a consequence, vehicles travel randomly within a given layout. This strategy is used as a worst-case benchmark that minimizes all routing decisions and necessary communication. Usually, other decentralized strategies at least make use of global information to some extent, i.e. the shortest paths between two points are known beforehand and the autonomous vehicles are able to directly or indirectly exchange their current statuses and intentions. Fanti et al. describe an approach where vehicles use an A* algorithm for individual route calculation [154]. During the execution of the routes, vehicles communicate with each other within a given radius, to synchronize and adjust the calculated routes. Digani et al. describe a routing procedure over two layers [167]. While only the large sections of a layout are accounted for in a so-called topological layer, the actual paths of each sector are considered in the so-called route-map layer. As a consequence, only the currently relevant subpart of a layout is taken into account for the routing procedure and deadlock avoidance, and is shared between multiple vehicles. Pallottino et al. describe a procedure for conflict avoidance and resolution between multiple autonomous, free-ranging vehicles, based on predefined rules and local information [168]. Schwarz et al. describe an approach where each vehicle is able to reserve time slots on single path segments [156]. Another vehicle has to take these reservations into consideration, when calculating its own route through the layout. Zhang et al. propose a CPS-based control for AGVs, which is responsible for the conflict-free movement of multiple vehicles in a dynamic shop-floor environment, especially at intersections [169]. In addition to a car-following strategy, prioritized AGVs are able to leave predefined paths and pass other vehicles. Single vehicles are able to communicate with each other if within a given radius, and are able to share "knowledge" in a database. Demesure et al. present a two-step approach for routing of free-ranging vehicles where, firstly, a central supervisor instance checks trajectories for conflicts and, secondly vehicles independently negotiate the right of way according to priorities, if conflicts occur [170].

Compared to vehicle-based systems, conveyor systems in general are a more static solution that reach higher throughput. Against the background of the autonomous paradigm, a conveyor can consist of multiple smaller modules that are responsible for their own decisions. Compared to the vehicle-based systems, the subproblems of routing and deadlock control also need to be covered for conveyor systems. Seibold and Furmans describe a decentralized sorting system, which consists of multiple rectangular decentralized transportation modules which form an omnidirectional surface [143]. For route reservation and deadlock avoidance they use the concept of logical time, which enables a synchronization of multiple processes. When planning a specific route via decentralized communication between the modules, the time stamps of other unit movements are put into a logical order. Therefore, each transport module is ascribed its own job order, which generally leads to the deadlock-free routing and sorting of the transportation units. A further approach using an autonomous conveyor system can be found in Gue et al. [171]. Krühn et al. describe a conveyor which consists of multiple small-scaled units that are able to move goods in an omnidirectional manner [172]. As the goods in transit are usually bigger than the autonomous units, multiple units have to dynamically organize themselves in groups. The route planning and reservation is performed in a decentralized way via communication between neighboring modules. Uriarte et al. describe a similar system of a cellular conveyor [173]. Multiple exchangeable, hexagonal modules are combined to an omnidirectional surface, enabling the goods to be transported and sorted. A camera system enables a visionbased feedback of the material flow [174]. All in all, the system combines central and decentralized elements. Via a self-developed communication interface, each element (cell) can communicate with all six neighbors and thus send commands from a central controller to the entire system in real time. In this way, the central part of the controller retains an overview of the entire process. The movements, however, are realized by the decentralized control boards installed in the elements (cells). Lau and Woo develop a method for a dynamic routing where multiple nodes serve as autonomous, cooperating agents [175]. They test their approach in a simulation model of a rectangular conveyor grid. Hallenborg develops an agent-based approach for routing in a baggage-handling system [176].

Figure 15: Main decision problems in intralogistics storage systems

2.2.3. Storage

Although goods are inactive while stored, there are important decisions to be made with regard to the storage of goods in warehouses. The three major issues are allocation, zoning and assignment [177] (Figure 15). Each of them can be operationalized into more specific subproblems, the solution to which has to be found by systems positioned at one of the Levels 2 to 4 in the automation pyramid (Figure 2). Such systems are generally gathered under the term automated storage and retrieval systems (AS/RS). It describes a group of systems that show a rather high degree of autonomy within their assigned scope of action, which is the fulfillment of storage and retrieval orders within a warehouse or production facility [178]. It is not without reason that the two subprocesses (storage and retrieval) are merged at this point, as they are strongly interconnected. The transport of goods also comes into play, but shall be looked at separately, as it constitutes a large category in itself, as described above.

When it comes to planning AS/RS, equivalent to Level 4 in the automation pyramid, some might question the need for such a system in a specific scenario, as investment costs are generally high and flexibility in terms of capacity adjustment is limited. Roodbergen and Vis give an overview of elements that need to be considered during design and operational phase of an AS/RS [178]. The authors claim that literature is too strongly concentrated on the analysis of AS/RS in static environments, and assume such environments to be reality. Instead, the authors suggest focusing on approaches that are more flexible. Volatile demands, changing order behavior and increased servicelevel requirements can thus be met. Dependent on the use case and frame conditions, it might be necessary to combine autonomous components with manual processes. For example, Russell and Meller focus on sorting as part of item retrieval [179]. The authors developed a cost-based optimization model to support companies in their decision whether or not to employ an automated system. One step further on from this, concepts like the multiparametric dynamic model of Manzini et al. come into play [180]. It allows an AS/RS to be designed, as well as the redesign and control of already realized systems, based on a what-if scenario analysis. Dependencies of the resulting systems performance from a multitude of parameters are also identified through the model. In addition, views that are more specific in terms of single-system components can be found in literature. One example is the analytical model by Malmborg [181]. It can be used for the assessment of suitability of an AS/RS with rail-guided vehicles instead of the commonly used aisle-captive cranes. Furthermore, the paper works out the superiority of analytical modeling as a chosen method, over simulation modeling. The main argument is the resource intensity of simulation modeling.

With regard to planning an AS/RS, the first step has been made, but now control demands attention. Control functions for storage systems can be assigned to automation Levels 2 and 3. In recent research, heuristics are scarcely mentioned as an approach for controlling AS/RS. Johnson evaluates two heuristics in the context of sorting items to orders [182]. The findings show that the superior sorting heuristic is dependent on the degree of lane blocking. Nowadays computational power is significantly higher and methods like computer simulation are commonly used. As well as the aforementioned model of Manzini et al. [180] there are other simulation-based approaches. One is presented as a decision-support system, which allows a rule-based equipment setup and thereby achieves increased efficiency in the controlled AS/RS. The benefits were proven via a computational simulation and a case study [183]. Similarly, Kim et al. employ simulation to verify their model concerning the design of ejecting zones on a conveyor, dependent on current type of a picking order in a warehouse [184].

After the planning and control of an AS/RS it might be necessary to optimize the system due to changes in factors influencing the initial system setup. Such planning in a long term reflects the idea of a Level

5 system in the automation pyramid. As mentioned above, AS/RS are limited in their ability to change capacity. These challenges can be met with the heuristic developed by Hackman et al. [185]. Its aim is to assign only specific items within a warehouse to the AS/RS, and for all other items to be handled manually. In contrast to this, Brezovnik et al. base their research on the assumption that all items can be handled by the AS/RS [186]. They show that a multi-objective ant-colony optimization is suitable for deciding on the distribution of items within the AS/RS. Further optimization can be achieved by implementation of novel robotic components, for example as described by Krug et al. [187].

2.2.4. Order Picking, Packaging, and Handling

As the basic functions ‘order picking’, ‘packaging’ and ‘handling’ show similar characteristics, we consider them together in this section under the term ‘handling’. The mentioned characteristics can be seen when looking at an abstract description of order picking, packaging and handling processes as in the following:

1) identification of a specific item to be picked/ packed/ handled,
2) grabbing/ removal of an identified item from location,
3) short-range transportation (e.g. from shelf to conveyor/ from order-picking cart to shipping box, and
4) positioning of item at target location

A main activity during intralogistics processes is the handling of items, for example either in the form of item retrieval from storage compartments during the order-picking process or during packaging and palletization. However, the development of autonomous systems in this field is a challenge accepted only in the last years. Bloss shows in his review that progress in programming as well as technological solutions for affordable, autonomous and versatile robots leads to an increase in applicability of autonomous systems in intralogistics [188]. Concurrently, speed as well as safety issues are still the main obstacles hindering an efficient application in practice according to Krug et al. [187]. Today, authors focus their research on systems that tackle both the transport as well as the handling issue [187]. For navigation, they employ a platform solution, which also detects humans, thus enabling hybrid warehouse operations. To plan and control the handling they use an algorithm introduced by Kanoun et al. that is based on a hierarchy of quadratic programs and shows real-time capabilities [189]. Kimura et al. present another approach to an autonomous system able to transport and handle items of different shapes and sizes in a warehouse similarly operated by humans and robots [190]. They put emphasis more on the handling of the storage boxes with two efficiently collaborating robot arms and a handover of items to the AGV than on the concrete gripping of the single items as in the aforementioned paper. Various designs of gripping hardware and related software to control the robots can be found in literature. Most of them come with constraints regarding flexibility in terms of shape, size, and fragility of items to be picked. Furthermore, special requirements may exist in terms of lighting conditions, the design of retrieval boxes or additional infrastructure might occur. Once the challenge of item identification and gripping has been overcome, assignment to boxes and packaging needs to be focused. Related problems are known under the terms ‘container-loading problem’ [191], ‘bin-packing problem’ [192, 193] and ‘pallet-loading problem’. In their reviews, Bortfeldt et al. [191] and Vargas-Osorio et al. [194] show the different problem types as well as the solution approaches focused on by researchers. Typically, the items to be packed are characterized as homogenous, weakly heterogeneous or strongly heterogeneous [191, 194] and come with several constraints such as orientation, stability, priorities and weight distribution [191]. Vargas-Osorio et al. also differentiate between two- and three-dimensional problems, and between exact, heuristic and simulation methods [194]. Examples for some of the mentioned problem specifications are given by Martello et al. who provide an exact solution to the three-dimensional bin packing problem [192] while Aringhieri et al. propose heuristic approaches [193]. Bódis et al. approached two intralogistics problems jointly – namely the pallet-loading problem and routing [195]. In their work, the impact of applying pallet-loading approaches to routing is analyzed. Their results show the necessity not only of optimizing the solution of a single problem but account for related problems simultaneously.

Overall, the developed solutions for planning, control and optimization are rather specific in application. Consequently, an autonomous system able to handle items with a humanlike flexibility and reasonable efficiency has not be found. One reason might be the restriction of the hardware’s abilities to grip a large variety of items. Another possible reason might be that by limiting the scope, the complexity of decision-making is reduced, which seems to be necessary at present. In conclusion, Levels 0 and 1 are seen as relevant for the systems currently used for order picking, packaging and handling.

2.2.5. Summary of planning, control and optimization methods

When using autonomous entities in a system, the decision-making is shifted from one central control unit to multiple autonomous decision-makers. This has multiple effects on the methods used for the planning, control and optimization of such systems. Firstly, the consequence that any alteration in one of the autonomous entities has on the overall system behavior cannot be predicted easily. Furthermore, conflicting actions can occur when multiple entities act autonomously while making use of shared resources such as space, transport means or similar. As a result, simulation models that are able to visualize the complex interdependencies are becoming increasingly popular. The method of simulation also allows an assessment of the application of a specific set of control algorithms. In terms of the practical implications, this means that there is a necessity for highly specialized professionals who can select and evaluate planning, control and optimization methods.

3. TRANSFORMATION INTO AUTONOMOUS INTRALOGISTICS SYSTEMS

3.1. Motivation and goals

Intralogistics systems consist of a wide range of consecutively and simultaneously running physical processes. At Level 0/1 the main processes transport, storage, picking, handling and packaging are executed. As a consequence, these physical processes and their connections must be designed to be autonomous to enable the system as a whole to be autonomous. This means that the performance and the decision-making competences must be transferred step by step from human operators to the machinery. As logistics systems focus on the execution of logistics processes, this chapter concentrates on the several automation stages for the Level 0/1 for each distinct subprocess by integrating sensors and actuators presented in chapter 2.

For each subprocess the following chapter primarily describes the requirements and challenges to enable further automation. These requirements lead to an adapted characterization of the automation stages. After a short overview of the current state of automation, the last paragraph concentrates on the application of the developed matrix of chapter 1 to the several process steps using specific use cases. Although these uses cases attempt to represent a high Stage of Automation, they don’t have to be best practices in automating the processes or, in section 3.3, systems. Since focus is on the classification matrix, precise knowledge of the automation steps of the single processes is more important.

The focus is on the specifics of the single subprocesses. This means that the components necessary for granting safety and communication amongst all participants are not considered in detail, since they are necessary for the performance of all processes. The identification and correction of mistakes is not the subject of detailed consideration in this chapter. To move from human operators carrying out processes to machinery doing so, the machinery has to be able to identify mistakes – deviations from the target situation. For a completely autonomous performance of processes, the system has to be able to handle deviations independently, without the help of a human in charge.

For the uniform and comparable description of automation stages, the following sections focus on the variance and the design of goods, the layout, the handling of known and unknown situations and the implementation of necessary methods. They are the basis for subsequently defining the state of the art in research and application, via use cases.

3.2. Transformation of distinct intralogistics processes

3.2.1. Transport

Requirements and challenges with regard to technology, control and communication

Intralogistics transport is crucial to many production and distribution sites. In production and cross-docking sites, warehouses and distribution centers, various goals of autonomous systems are focused. The main objective is to increase the efficiency of transport systems. Thus, it is important to ensure an economic and flexible in-house material transport with a high service level. Increasing variety, smaller order quantities and the associated production of smaller batches are just a few challenges facing economical and flexible (autonomous) transport systems in intralogistics [196, 197].

According to [198], the following are of relevance to the planning of transport systems: the utilization (e.g. minimal transport costs, high functional and temporal utilization), service level (e.g. short order waiting times, fast response to urgent transports), flexibility (e.g. wide range of different goods) as well as transparency and controlling (e.g. information about current situation, availability, location, executed orders, data collection, key figures) of transport systems. There are various material-handling technologies used to execute intralogistics transport. When using them, information retrieval and data processing from the enterprise resource planning (ERP) system, Manufacturing Execution System (MES) and shop-floor systems (e.g. dispatching, scheduling and routing in the system at 1 to n units) concerning the source, drain and transported object is necessary. To ensure a safe transport process, the test and measurement technology for the observation of the transported objects or the environment must be considered as well. The operation of transport processes also requires the execution of steering, flashing, acceleration and braking maneuvers (see section 2.1) [199, 200, 201, 202].

Automation stages

Stages 1 and 2 require a greater influence of humans on the transport system. At Stage 3, the influence of human beings continues to decline whereas the sensory and actuator intelligence of the vehicle increases. From Stage 4 onwards, the possibility of system-wide communication between the vehicles and the

Table 3: Description of the automation stages for the transport process

Stage	Name	Description
Stage 0	No Automation	– Manual execution of all process steps, probably using manually powered equipment
Stage 1	Assistance Systems	– Actuators (for motion) enable empowered vehicles
Stage 2	Partial Automation	– Basic sensors (e.g. for safety or identification) support the individual driver and lead to accident-avoidance technologies
Stage 3	Conditional Automation	– Identification of known objects is possible – Sensors and actuators interact, therefore control functions work together to relieve the operator of some controlling functions in infrequently changing environments. This enables automated, but track-guided vehicles to be used
Stage 4	High Automation	– Complex sensor and simple decision technologies enable complete control in infrequently changing environments and therefore non-track guided vehicles
Stage 5	Autonomy	– Reliable location and object identification lead to autonomous driving even in highly complex and dynamic environments

system begins (e.g. as a multi-agent system) which enables more flexible transport systems. The detailed description of the automation stages is given in Table 3.

Current state of automation

For nearly all applications, powered vehicles are now used, therefore Stage 1 can be considered as state of the art. However, since their introduction in 1955, AGVs have become increasingly important in industrial applications [152]. As most of them have been track-guided, they are examples of vehicles at Stage 3. These track-guided vehicles only need simple sensors for (mostly frontal) object identification and sensors for lane recognition. As the requirements for object identification and localization are increasing for non-track-guided AGVs, they are primarily used in outdoor applications without human interaction. For indoor application, digital map material and a local localization system form the basis of non-track-guided AGVs. To increase safety, cameras and laser scanners as well as communication networks (i.e. WLAN, 5G) are necessary. Together with routing and bypass algorithms, the fourth stage has also been reached for transportation networks. The following use case presents an example of highly automated transport in outdoor industrial application.

Use case

As part of a pilot application for automated trailer yards within the automotive industry, the AutoTrailer (Figure 16) is an automated guided vehicle capable of moving semi-trailers from the yard to dock doors. This use case was selected as it illustrates the current level of automation of outdoor AGVs in real applications. The localization and navigation of the AutoTrailer are performed by LiDAR scanners as well as SLAM. Docking and undocking of semi-trailers is fully automated and without any human intervention. Moreover, the AutoTrailer operates in a dynamic environment which includes other traffic and human beings. To be safe in this dynamic environment, the AutoTrailer has five certified outdoor scanners, four on each corner of the vehicle and one on the extended unit. A telescopic mast on the rear side of the vehicle is extendable and extends underneath the trailer to the rearmost axle. Thus the AutoTrailer is able to secure the entire rear side as well as the sides of the semitrailer. The AutoTrailer follows only predefined routes that have previously been entered into the path control unit by humans. If something or someone blocks the path, the AutoTrailer is not able to move around. It stops and waits until the obstacle is removed or for a relevant signal from the human beings. With reference to Table 3, the operation of the transport process (Level 0/1) can therefore be classified as Stage 4. If problems occur, the AutoTrailer sends signals to the human operator so that he can react and make decisions (Stage 3 for Level 1). The AutoTrailer is controlled via a control system that is partly centralized (Stage 2 for Level 2). To place an order with the AutoTrailer, an employee chooses a certain yard slot and dock door on the user interface of an industrial control panel. However, the employee can only choose from a limited number of routes which have previously been input. The AutoTrailer is not able to make decisions, but it can support decisions (Stage 1 for Level 3). The overall planning must be carried out by humans (Stage 0 for Level 4). Figure 17 presents a summary of the achieved stages for each level.

Figure 16: AutoTrailer

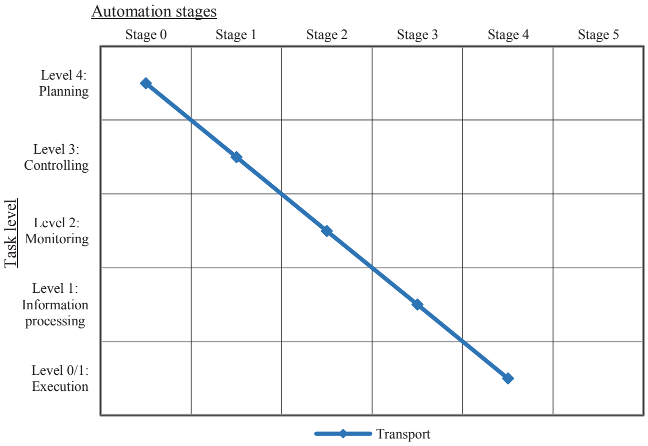

Figure 17: Evaluation of the AutoTrailer using the proposed classification matrix

3.2.2. Storage

Requirements and challenges with regard to technology, control and communication

Regarding the operational task, the storage process is subdivided into the following process steps: receiving, storing, order picking and shipping [203]. However, in order for organization to be included as well, the processes "incoming goods inspection, […] inventory management, inventory control and stocktaking, and maintenance of the equipment" [204] must also be considered.

According to Fischer, in order to execute the object identification, the space allocation is necessary, as is the verification and checking of the storage location [205]. While the object and storage location identification require sensors, the space allocation is a decision problem, and more precisely one of the assignment problems mentioned in section 2.2.4 [177, 206].

According to Gu et al. solving this storage location problem, requires the following data:

- "Information on the storage area including its physical configuration & layout
- Information on the storage locations, including availability, physical dimensions, location
- Information on the set of items, including physical dimensions, demand, quantity, arrival, departure times" [177].

While information regarding the storage area, configuration and layout of the storage location do not change permanently, the information concerning the availability of the storage location and the set of items constitute permanently. A high accuracy of such data must therefore be guaranteed during execution. The other information mentioned must be detected by the object-identification system. Depending on the range of sensors used, data synchronization with the central data base could be necessary. After transporting the goods to the storage location and before storing them, the storage location must be verified and checked. This requires on the one hand sensors for localization and on the other hand object-identification sensors to ensure an empty storage location. The abovementioned demands result in the necessity for sensors in the execution of the storage process for object identification and localization, as well as consequent communication with the system as a whole in terms of the free and empty storage locations.

The several automation stages can be adapted to the storage process with regard to these process steps, the information required, the sensors used and the decision problems.

Automation stages

At the lowest grade (Stage 0), manually operated means of transport and/ or handling (e.g. platform trucks, forklift trucks or scissors lifts) support the human operator during the storing and retrieval processes. As soon as these means are motorized, the first stage of automation is reached. Simultaneously, simple auxiliary systems for storage allocation and/ or inventory management can be used. At the next stage (Stage 2), sensors are used to automate some process steps (e.g. object identification) as well as the allocation. Whereas a rough localization leads to automated vehicles for simple routes, the exact positioning and storage-location verification and therefore the storage process is still effected by the human operator (Stage 3). At the penultimate stage, the whole storage process is effected by an automated system, if the stored goods are standardized and/or well known. A short description of these stages is given in Table 4.

Table 4: Description of the automation stages for the storage process

Stage	Name	Description
Stage 0	No Automation	– Manual execution of all process steps by humans, probably using manually powered equipment of transport and/ or handling
Stage 1	Assistance Systems	– Manual execution of all process steps – Due to actuators for transport and handling, motorized equipment of transport and/or handling is possible
Stage 2	Partial Automation	– Basic sensors for object identification using labels – Interaction of localization and identification sensors with the actuators leads to automated execution of single process steps, such as transport
Stage 3	Conditional Automation	– Rough localization enables autonomous transport vehicles – Exact positioning as well as storage and retrieval is still performed by the human operator – Automatic object identification, allocation and handling of standardized, known goods
Stage 4	High Automation	– Highly automated storage and retrieval of standardized, known goods in static environments – Extraordinary situations covered by human operator
Stage 5	Autonomy	– Automatic object identification, allocation and flexible takeover of several kind of goods – Autonomous storage and retrieval

Current state of automation

In practice, storing is already one of the highly automated processes. Automated small-parts warehouses and highrack warehouses as well as container terminals without any humans are state of the art nowadays. This high stage of automation is facilitated by the use of uniform loading equipment (such as pallets, containers or small-parts containers). They enable standardized processes, the use of simple sensors and actuators as well as unique materialhandling systems. For example, simple barcode and laser scanners can be used for object identification at the warehouse entrance [207]. Simple photo sensors can be installed at necessary heights of the shelves' entrances to register the access and outflow of goods in order to determine the storage location's availability, and simple laser and distance measurement can be used for the final consistency check before storing. The used warehouse management systems enable highly automated storage and removal, as well as real-time monitoring for the operator; however, adaptation to changes is not yet automated, so such systems can be classified as Stage 4. Such high-level automation is however only possible for standardized loading devices. If the variety of objects increases, the level of automation mostly decreases. This leads to a classification of most systems within Stages 1 to 2. The following use case describes a research application which projects towards a completely automated transport, storage and handling system.

Use case

A further example of an application of automated intralogistics processes in outer areas, which additionally deals with a 3D-storage system, is a pilot plant created at the EUROGATE Container Terminal Wilhelmshaven (CTW) Its goal is to provide technical proof that the automated transport, storage and handling of containers via driverless straddle carriers (Figure 18) are possible [208]. Besides the transport and storage processes, it therefore also includes the loading and unloading of ships, trains and trucks. The straddle carriers execute the required transportation process within a familiar environment without human participants (Stage 4, Level 0/1). A local antenna system is used to ensure an exact localization of the straddle carriers. It consists of antennas that communicate with each other and synchronize their time stamps. Analogous to the GPS localization, but in receipt of more precise information, an onboard module makes use of the signals of the antennas to calculate the actual position of the straddle carrier. The carriers use proximity sensors, light barriers and laser scanners to identify the required container. However, for the purpose of problem solving and exact positioning for takeover, a remote control system in the control room launches, for manual control the straddle carriers (Stage 3, Levels 0/1 and 2). Although the straddle carriers independently send actual status information, and requests further orders (Stage 3, Level 2), human operators assign the incoming tasks with a start and end position for a specific container to the

Figure 18: *Straddle carrier (Photo: Sabine Nollmann)*

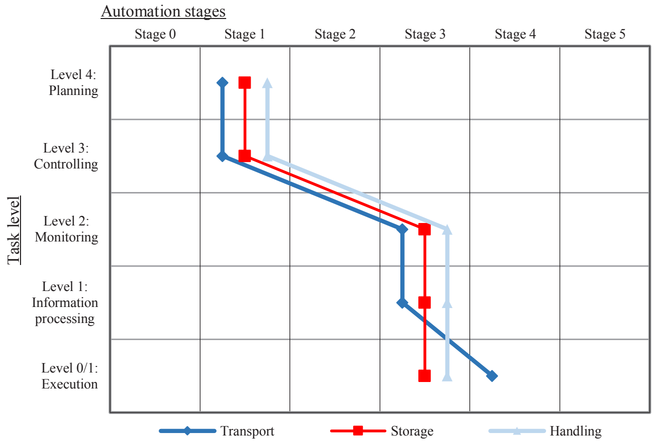

Figure 19: Evaluation of the unmanned straddle carriers plus IT infrastructure using the proposed classification matrix

several straddle carriers via a Terminal Operating System (Stage 1, Level 4). The sent routing information and positioning data for each straddle carrier uses a central Fleet Control Management System to calculate the required route between start and end position for each of them (Stage 1, Level 3). A summary is given in Figure 19, which presents the achieved stages for each level.

3.2.3. Order Picking

Requirements and challenges with regard to technology, control and communication

The aim of order picking is the compilation of goods from a total stock on the basis of defined orders. This order processing can take place in different forms and, in the current development, it is not only linked to purely orderrelated picking [209]. The provision of goods can be done centrally ("goods-to-person") as well as locally ("person-to-goods"). The identification of goods at the storage location can take place via mobile or stationary terminals, mobile data acquisition (MDA) or pick-by-x (voice, light, list, point etc.) [210].

Current topics deal with further order-picking strategies such as multi-level picking, which splits orders more efficiently into partial orders [211, 212], or the support of novel technologies for the order- or article-oriented, parallel or serial, person-to-goods, goods-to-person, person-to-person strategy [213], as well as the use of modern picking robots. The use of a warehouse management system (WMS) or ERP system forms the basis for ensuring the availability of materials/ items for picking.

The picking process steps are summarized according to [209]. The listed process steps are given for orientation purposes, and can be customized within the company. It can be seen that the basic processes of storage and order picking are closely linked. This leads to similar requirements for sensors as well as the communication with a central system. According to [214], criteria such as the heterogeneity of orders, heterogeneity of the range, scope of services, distance associated with a picking order, masses and volume of articles to be picked can have an influence on order picking. As mentioned above, order-picking systems additionally deal with picking strategies. As the implementation of most strategies is complex, the decision is made strategically by human planners. In the context of increasing automation and the use of modern assistance systems, future systems have to be able to select the best picking strategies on their own.

Automation stages

Whereas all process steps are done manually at Stage 0, motorized equipment as well as information technologies for picking instructions enable a higher automation stage (Stage 1). The technological possibilities at Stage 2 enable an automated execution of several process steps, but direct cooperation starts at Stage 3. Further automation solutions change the information technology used and the execution of physical functions of the picking activity. Therefore, the basic functions of storage and picking tend to be more strongly linked in the higher stages of automation. The classic separation between the entry and exit of picked goods no longer occurs at Stages 4 and 5. A detailed description of the automation stages is given in Table 5.

Current state of automation

As mentioned in chapters 3.2.1 and 3.2.2, there are high automated transport and storage processes, especially for standardized products. However, in addition to the requirements given in the previous chapters, more precise object detection and object localization are necessary for order-picking processes. As long as standardized products with guaranteed individual access have to be picked, simple sensor technologies enable a high automation stage up to Stage 4. However, in most cases, this is not the case. There is a high variability of products and due to a

Table 5: Description of the automation stages for the order-picking process

Stage	**Name**	**Description**
Stage 0	No Automation	– Manual object input and output – Handling instructions are transmitted via picklists – Transport and handling may be supported by using a manually operated transport unit
Stage 1	Assistance Systems	– Manual object input and output – Instructions are transmitted via an information technology assistance (pick-by-x) – Transport and handling may be supported by using motorized transport units
Stage 2	Partial Automation	– Motion and transport actuators facilitate support for object input and output – Transport and handling are supported (e.g. by storage location search)
Stage 3	Conditional Automation	– Partial cooperation in input and output between human and technology for piece goods – Separation between storage and picking partially available – Instructions for action are given via an information technology assistant to the technology used – Automated transportation and handling
Stage 4	High Automation	– Input and output of known goods is done by technology – Human operator takes over controlling activity – Separation between storage and picking is no longer available – Handling instructions are processed independently by the technology used – Autonomous transportation and handling of known goods
Stage 5	Autonomy	– Automatic object identification, allocation and flexible picking of several kinds of goods – Autonomous storage and retrieval

missing individual access, even the exact position and orientation of these products have to be identified. This requires precise sensors, gripping algorithms and gripping technologies, that do not exist in the necessary combination. Therefore, the current state of automation for a high variability for most application remains at Stages 1 or 2. Where the variability of products cannot be handled by a robot itself, humans will be necessary to ensure order-picking processes. This leads to a need for safety sensors, to ensure a greater collaboration between human and robotics within the order-picking processes. Even intelligent and networked machines and algorithms, which not only support, but also learn by themselves, are possibilities to increase the automation stage. Thanks to the support of robotics, the picking strategies tend towards a goods-to-person or goods-to-robotics strategy. An example of high automation and collaboration with humans is presented as a use case.

Use case

A combination of high automation in storage and picking is often seen in the pharmaceutical industry. Such orderpicking machines are generally used when automatically handleable products have to be picked at maximum unit output. Over 40,000 cylindrical or cuboid products can be picked per hour, as these usually small and standardized products are known to the machines. Another example of high automation in picking is TORU, a picking robot of Magazino (Figure 20). These robots combine picking with retrieval and transport processes. Both the transport and the picking process are autonomously executed within a familiar and dynamic environment. However, as the picked goods are known products in cuboid format, and the number of human participants is restricted, both processes are classified at Stage 4 for the execution (Level 0/1). Whereas for transport processes TORU communicates with the central fleet management regarding its status and position during the process (Stage 3, Level 2) information concerning the picking process is transferred only after specific actions (Stage 2, Level 2). The robot locates objects to be picked with 2D and 3D cameras, using intelligent algorithms to search for the barcodes, and can thus identify the correct object (Stage 3, Level 3). Due to its high automation in execution, some decisions in the overall system planning processes are also made by a central system (Stage 2, Level 4). Figure 21 summarizes the classifications in the proposed matrix.

Figure 20: Picking robot TORU of Magazino [215]

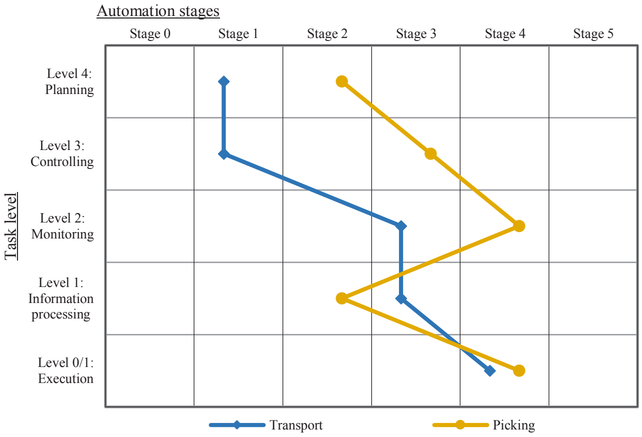

Figure 21: Evaluation of the picking robot using the proposed classification matrix

3.2.4. Handling and packaging

Requirements and challenges with regard to technology, control and communication

As mentioned in section 2.2, packaging and handling have similar characteristics in terms of planning, control and optimization. Nevertheless, as will be shown in the following paragraphs, the process steps and therefore their technological requirements and challenges are also nearly the same.

During the packaging process, a package is assembled by merging the packaged good and the packaging, including the wrapping and the packaging aid [216]. There are three different stages of packaging to be distinguished. They are "typically classified into primary (product), secondary (retailer) and tertiary (transport or logistical) packaging" [217, 218]. Hence, the packaged goods could be single elements or a combination of elements, or even bulk material. As the packaging of bulk or liquid material requires different process steps, this paper focuses on the secondary and tertiary packaging. Therefore, only the packaging of general cargo is considered.

Before packaging the goods, they have to be, if necessary, sorted and portioned [219]. As well as the packaged good, the packaging material has to be prepared, including, if required, preforming and supplying [4]. After portioning, the piece goods are transferred to and enclosed by the packaging material. To ensure identification, labels have to be attached to the packaging material [220]. All mentioned process steps are part of the handling process, as the relevant process steps are the separation of goods (if necessary), grasping, moving, placing and dropping [221, 222, 223]. Therefore, merging the packaged goods and the package is part of the handling process. The goal of the handling process is to create or to retain a determined spatial arrangement of goods [222, 224]. While the position is predetermined during the handling process, similar to the packaging material, it must be predetermined in the packaging process by solving various assignment problems (see section 2.2.5). Depending on the requirement, this calculation is necessary only once for the various articles (combinations) or at the beginning of a packaging process. Table 6 presents the requirements to be performed by handling processes; the specifics of the packaging processes are written in italics.

As with the other processes, object identification is necessary before starting the process. However, as the exact position and orientation of the object is necessary for grasping, localization technologies are also needed. After the successful identification, calculations concerning the grasping position [225], the dropping position and the trajectory [225] have to be performed. Further localization technologies for the gripper and the dropping position are necessary. To avoid damaging the goods the robot needs condition sensors (specifically: force sensors).

Automation stages

At automation Stage 0, humans perform all decisions and are also responsible for object manipulation. Technical systems help humans, especially with handling heavy parts. At the next stage, the first process steps are taken over by technical systems, but without recognizing objects. However, after entering object-specific data, the systems can assist in grabbing or moving the goods, e.g. machines that unfold standardized packaging material such as cartons, and make it available to the packer.

The systems independently take charge of the use of sensors and individual functions such as handling, gripping or positioning. In high automation, human beings are now primarily responsible for supporting the technical system, e.g. the supply or delivery of goods. They must interfere if e.g. objects are still unknown or if they do not have the expected location for the

Table 6: Description of the automation stages for the handling process

Stage	**Name**	**Description**
Stage 0	No Automation	– Human operator chooses and manipulates objects using mechanical means of handling
Stage 1	Assistance Systems	– Powered means of handling wait at standardized positions for further instructions to help the human operator
Stage 2	Partial Automation	– Primarily usage of sensors for object identification using aids (as markers, codes or labels) – Actuators for motion facilitate the execution of single process steps – *Autonomous presentation of standardized packaging schemes after object identification*
Stage 3	Conditional Automation	– Primarily usage of sensors for object identification and localization enable the linking of several process steps – Human operator executes complex processes – *Presentation of different packaging schemes and materials after object identification (and if necessary localization and condition monitoring)*
Stage 4	High Automation	– Known objects are autonomously identified (using a database) and handed over to known positions on known paths – Unknown objects, positions or paths have to be trained – Human operator controls process – *Autonomous packaging materials and schemes calculation*
Stage 5	Autonomy	– Autonomous execution of all process steps – *Autonomous packaging materials and schemes calculation and adaption*

system. The autonomous system, however, can solve all problems independently. It can thus recognize all incoming goods and put them in the right position.

Current state of automation

To handle standardized objects (e.g. bins or packages), simple methods of object detection, such as light barriers or laser scanners in combination with labels are sufficient. The handling of single and maybe irregular products requires more precise object-identification technologies, such as camera or ultrasonic sound technologies. To localize these objects and position the gripper, complex laser systems (e.g. LiDAR) or infrared technologies measure the distance between object and gripper. To ensure higher precision in object identification and localization even for smaller objects, more complex systems combine several technologies (e.g. camera and infrared sensors). The gripper localization started with internal angle calculations, but for more precise localization, the robot uses localization technologies (as mentioned in chapter 3.3.1). The fact that industrial robots have been used in production processes for many years already facilitates the highly automated calculation of trajectory and position.

Use cases

An example of a robot that can grip precisely and transport at the same time is shown in Figure 22. The service robot consists of a transport platform and a manipulator. The main task of the service robot is to take over all transport processes in the tool cycle within the scope of tool logistics. The manipulator is equipped either with a universal or with an interchangeable gripper to handle different kinds of tools. The transport platform, which is connected to the manipulator, has guidance-free navigation. Using laser scanners, the robot creates a 2D map in which important points are added in a second step. After the transmission and storage of the map, the robot is now ready to use the map to find its way around the environment and to move to the required positions. If obstacles such as objects or humans en route cannot be avoided, it then takes an alternative route (Stage 4, Level 0/1). The planning, control and prioritization of service orders are implemented by humans using a central ERP system (Stage 1, Levels 3 and 4). In addition to the transport, the implementation of handling processes of various ranges is required. Although the service robot is able to pick up tools from a workbench, it does not secure human intervention in the gripping process. Hence, the service robot is not collaborative, which leads to a lower classification (Stage 2, Level 0/1). Moreover, the robot needs assistance in monitoring the environment (Stage 2, Level 2). Although the service robot sends status information, it cannot request further orders independently and hence cannot interact with the central system (Stage 2, Level 1). Figure 23 gives an overview of the classification of the service robot.

Figure 22: Service robot [226]

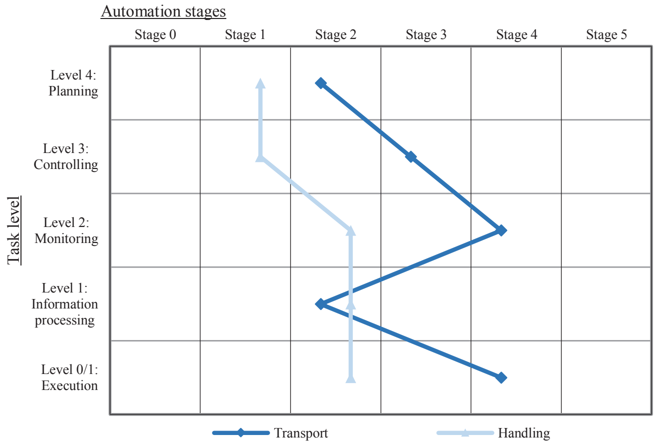

Figure 23: Evaluation of the service robot using the proposed classification matrix

3.3. Transformation of whole intralogistics systems

For designing automated intralogistics systems, it is necessary to connect the main processes. For reaching the stage of high automation for the whole logistics system, all main processes included have to be from Stage 4 as a minimum for all levels. The intralogistics system becomes autonomous only if every single main process matches Stage 5 at all levels. Considering inbound as well as outbound processes, a limitation for certain groups of goods or certain material-handling systems can be made. For example, inbound logistics for small parts containers can be highly automated, whereas the supply process for production lines involving heavy load containers is only partially automated.

During recent years, there has been a trend towards automation in intralogistics for a number of reasons. One of the reasons mentioned very often by companies is the lack of skilled workers. Further reasons include the dynamics of supply processes or the reduction of the error rate. Nonetheless, within a few companies, including OEMs, it has been noted that their intention is for production supply to be as automated as possible. Whereas the operational level in reality of most inbound and outbound systems within companies is located at Stages 3 to 4 at a maximum, the upper levels remain at Stages 0 to 2. With pilot projects, leading logistics companies try to reach Stages 3 and 4.

Use cases

Automation in inbound logistics

The supply of small parts for the series production of chassis constructions at an automobile manufacturer is an example of well-advanced automation. Small parts for chassis construction are provided in three standardized box sizes in shelves. Incoming goods are delivered on homogeneous pallets in small parts boxes. The truck is unloaded manually with forklifts (Stage 1, Level 0/1). Afterwards, pallets are brought by the forklifts to a workplace (Stage1, Level 0/1). At this workplace there are robots for automatic depalletizing. Using sensor technology, they automatically recognize three different box sizes and various ways of stacking, and depalletize layer by layer by putting the boxes on roll conveyors (Stage 4, Level 0/1). Via the roll conveyors, the boxes arrive at a point where they are weighed automatically and the articles are identified by barcode (Stage 4, Level 1). Defective boxes (e.g. no identification possible or boxes are too heavy) are removed and have to be handled manually (Stage 4, Levels 1 and 2). Verified boxes automatically reach the transfer point of the automated small parts warehouse which is not working as a classic warehouse, but as a picking warehouse. Warehouse shuttles for small parts – having been placed onto the relevant level by vertical conveyors – drive through the individual areas of the warehouse. The whole process of storage and retrieval with election of the shelf, the lateral distribution over the warehouse areas and the use of storage strategies such as first-in-first-out or doubles (storage and removal with one shuttle), are executed in a completely automated manner (Stage 4, Level 0/1). About three hours before the goods are needed on the production line, the removal process is triggered by the MES. Highly automated, the MES generates the removal orders and allocates the boxes to single tugger trains. The WMS uses this information to generate retrieval orders released by an employee (Stage 2, Level 4). The boxes, removed by the shuttles, are automatically marked with a barcode for later allocation to the relevant tugger train, and transported via roller conveyors to sequencers. Each “sequencer” consists of a shelf with a robot. After object identification, the robot requests the storing position from the MES (Stage 4, Level 2) automatically pre-sorts the boxes for up to two tugger frames by storing them temporarily

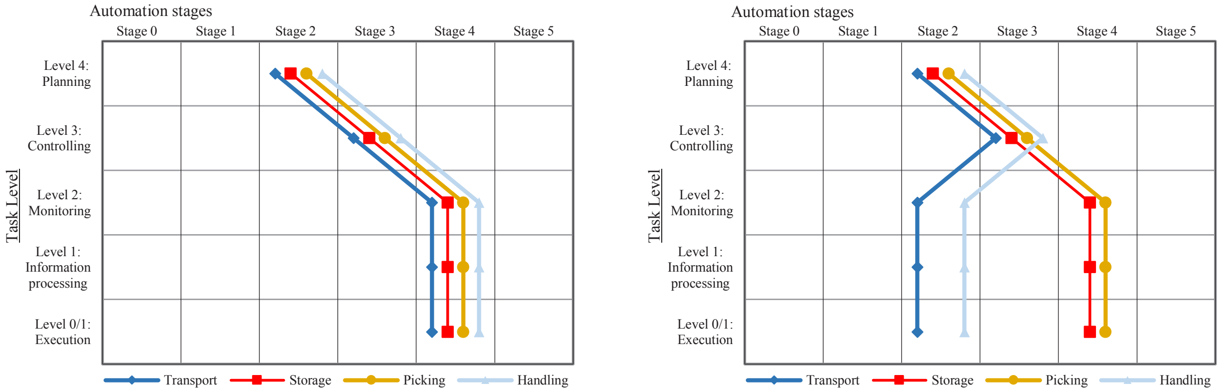

Figure 24: Evaluation of the intralogistics systems (depalletizing until loaded tugger frame on the left and complete inbound logistics on the right) using the proposed classification matrix

in a rack (Stage 4, Level 0/1). As soon as an empty tugger frame arrives at the "sequencer", the robot gets information from the tugger train (Stage 4, Level 1) and then loads the tugger frame automatically. After being loaded completely, the robot signalizes release for picking-up by the tugger train. Although, in this case, the tugger train is driven by an operator, the processes loading and unloading the trailers using tugger frames is done semiautomatically using assistant systems (Stage 2, Level 0/1). The transport of the boxes with the tugger train and sorting the boxes into the shelves of production is also a manual process. The classification of the transport and handling process into the stages of automation depends on the definition of the system boundaries. The execution of all processes from depalletizing to the provisioning of the small parts boxes in the tugger frames, including information processing and monitoring, are highly automated (Levels 0/1 to 2, Stage 4). Widening the focus in terms of inbound logistics from the point of incoming goods to the supply of the production line, the processes for transport and handling only reach Stage 2 for the Levels 0/1 to 2, because of the manual execution at the end and beginning. Within the mentioned boundaries, central systems for each process are used for controlling and planning. Whereas human action is required to start orders (Stage 2, Level 4), the controlling of processes does not require any action (Stage 3, Level 3). The evaluation of the variants is displayed in Figure 24.

Semi-automated dispatch process

Although many process steps for standardized products in dispatch processes of logistics service providers are already highly automated, several steps still require manual execution, as described in the following example.

The incoming goods that are not larger than a predefined size are loaded manually onto telescopic conveyors. If the packaging box is too large, the goods are repacked manually into smaller boxes and then loaded onto the conveyors. They transport the goods directly to the automatic high-bay warehouse, which stores and removes the boxes automatically. Goods that are too large for the conveyor system are manually handled and hence are not considered here. After the automatic removal, the cartons and boxes are transported by the conveyor system to the picking area, where they are manually prepared for the picking process. While a software system decides on the exact location, the positioning of the boxes is executed manually by operators. For removal processes, the system generates picking lists that are handled by the picker with a roll trolley. When removed, articles are manually marked with an identifying label and loaded into transport boxes. After picking, goods are handed over to a conveyor system by the picker and are subsequently transported into a buffer store (either roll conveyors or automated small parts warehouse). If all goods for a removal tour have arrived, the boxes needed are automatically removed from the buffer and transported to the sorter. The sorter automatically assigns the articles to the customer order. For the sorting process, boxes are emptied automatically at workplaces in front of the sorter and the articles are placed manually, barcode turned upwards, on the conveyor belt that leads to the sorter. By doing so, they can be individually registered and allocated to the corresponding shelf space. As soon as all articles arrived, they are manually packed and marked with the corresponding dispatch label. Later on, packed cartons are automatically tied up and transported to the relevant dispatch area.

The evaluation scores for the process steps display a wide range. Whereas the execution of transportation and storage processes is highly automated (Stage 4, Level 0/1), picking processes are performed manually (Stage 0, Level 0/1). Technical solutions are usually only used for support. Many handling and packaging process steps are executed manually, but the high automated sorting process before packaging as well as the automatic lacing enable a higher stage (Stage 2, Level 0/1). Although the evaluation score of the execution differs significantly, all subprocesses achieve a similar score for the upper levels. All processes except the picking process, have assistance systems during the execution and therefore are classified into Stage 2 for the Levels 1 and 2. During the picking process, a manual picking list is used and so it receives a lower evaluation score (Stage 1, Levels 1 and 2). Controlling and planning for all processes are effected by humans with the aid of decision systems (Stage 1, Level 3 and 4). To sum up, Figure 25 renders the evaluation scores of the distinct process steps and therefore of the intralogistics systems.

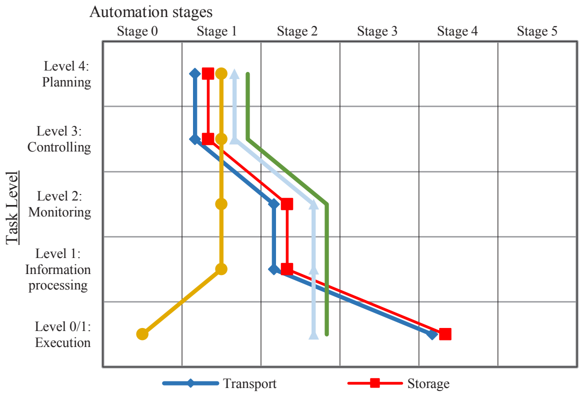

Figure 25: Evaluation of the dispatch process of the logistics service provider using the proposed classification matrix

Automation of the entire material flow of an automotive manufacturing plant

An automotive manufacturer is planning the complete automation of intralogistics. From inbound up to outbound, a wide variety of robots and AGVs, which handle different logistics tasks, are to be networked. Thus, this use case was chosen to illustrate the full automation of the complete system. To guarantee a smooth material flow, inherent safety, an intuitive operating concept and intelligent algorithms are required.

Although some components already exist, no system is yet in use. Hence, the planned execution of the processes is as follows: After the arrival of the trucks, they park their semi-trailers on the factory premises. An outdoor AGV docks and transports semi-trailer independently from a yard to the docks or vice versa. The positioning and docking of the semi-trailers is automated. An automated indoor as well as outdoor forklift unloads the semi-trailer. Subsequently, the forklift transports the pallets to an AS/RS. Subsequently, a depalletizing robot with a mobile platform and a manipulator on top separates autonomously – by using a vacuum gripper – several boxes from the incoming pallets. After that, the small boxes go either to the picking area or straight to the assembly line. If the boxes need to go first to the picking area, an intelligent pick robot picks individual containers. If the boxes from the AS/RS need to go straight to the assembly line, an automated guided vehicle, that navigating through the factory without any physical guidelines (only with SLAM), takes the supply racks with several boxes and transports them to the assembly line. In some cases, boxes arrive at the assembly line via automated tugger trains – in these cases a mobile handling robot takes over the boxes from the tugger train and transports them straight to the supply racks at the assembly line. For the handling of the empty boxes, a palletizing robot stacks the individual containers on a pallet. Then, a fully automated mobile platform with a capacity of 20 pallets transports the pallets from the indoor to the outdoor area where they are returned to the semi-trailers of the suppliers.

Although the execution of the transportation process is planned as an autonomous process, the execution of the picking and the handling processes can only be evaluated as highly automated, as they only handle standardized and known containers (Stage 4, Level 0/1). This fully automated flow of material (with all the associated communication, controlling and safety tasks) is connected via the new mobile standard 5G. It enables lower latency and faster data transfer, and connects robots and AGVs outside and inside of the factory halls. All robots that take over handling, picking, and transport tasks are equipped with object detection by cameras. Vision algorithms in combination with Artificial Intelligence (AI) provide robots with the opportunity to act independently. But because of the higher execution level, the transport system is able to generate and acquire information, and share some of it with the central system (Stage 3, Level 1), whereas the other processes only propose assisted information acquisition (Stage 2, Level 1). Human operators have control and maintenance functions for the picking and the transport processes (Stage 1, Level 3) and controlling functions only for the handling processes (Stage 2, Level 3). With mobile devices, e.g. mobile phones, smart glasses or touchpads, human operators

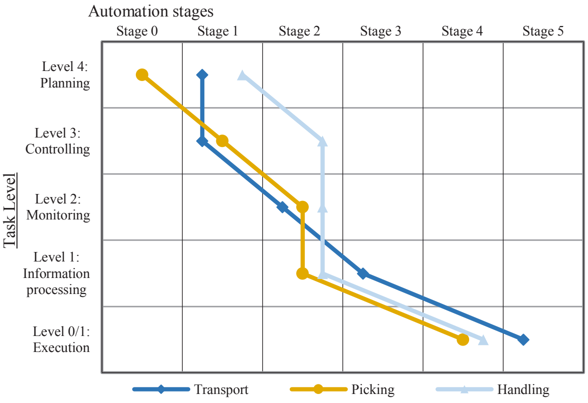

Figure 26: Evaluation of the planned material flow system using the proposed classification matrix

can check the status of every single system on the factory premises at any time (Stage 2, Level 2). Hence, they are able to make either manual decisions for picking, or use decision-support systems for transport and handling processes (Stages 0 and 1, Level 4). Figure 26 presents the evaluation of the planned system.

3.4. Summary

To classify an intralogistics system, it is necessary to analyze the main processes regarding their automation stage for the different task levels. In classifying the executional level (Level 0/1), sections 3.2.1 through 3.2.4 present a description over all the automation stages for each main process. To facilitate the classification into the several automation stages, the following Figure 27 provides some technical solutions especially for the operational level of the processes (Level 0/1).

As shown in the previous sections, the degree of automation of the individual basic functions varies. From no later than the third stage onwards for the first level, a higher degree of automation requires at present, a higher degree of standardization. The reasons for this are, on the one hand, the still insufficient object recognition, the necessary specialization in object manipulation and the decision algorithms, which still require user input in unknown situations.

This leads to a wide range of automation stages in application. As the presented use cases in section 3.3 shows, companies in the automotive industry in particular have highly automated processes. In other sectors, manual execution is still of great importance.

4. OUTLOOK AND FUTURE CHALLENGES

After this detailed examination of the term autonomy in relation to intralogistics systems, the presentation of various examples, a development of a comparatively suitable representation of the degree of autonomy of different components in logistics systems, the following chapter 4 looks visionary into the future. The intention is to provide an open view of the future rather than a further summary of development trends that are already foreseeable today.

4.1. Achievements in autonomy and control issues

In order to reach autonomy in intralogistics, services are required at various levels. At the level of intralogistic elements (individual vehicles etc.) autonomous solutions are already being applied in practice. A frequent application are so-called ATVs (Autonomous

Automation Stage					
5					
4	Non track-guided AGV	Automated storage and retrieval system	Autonomously driving picking robot	Robotic (de-) palletizer for cubic elements	Packaging robot, Automated packaging machine
3	Track-guided AGV	Automatically following vehicles	Automatically following picking vehicles, stationary picking robots	Robotic (de-) palletizer for repeating problems	Packaging machine for standardized products
2	Forklift or tugger train with assistance systems	Forklift or reach truck with assistance systems	Pick-by-voice systems	Manipulators, scissor lifts	Carton erectors
1	Forklift, tugger train	Forklift, powered manipulators	Forklift, order pickers	Powered manipulators, scissor lifts	Powered manipulators
0	Mechanically driven platform trolley	Mechanically driven platform trolley	Mechanically driven platform trolley	Mechanically driven manipulators for heavy goods	Mechanically driven manipulators for heavy goods
	Transport	**Storage**	**Order picking**	**Handling**	**Packaging**

Figure 27: Exemplary classification of technologies in the automation stages of the main processes

Transport Vehicles or AIVs – Autonomous Intelligent Vehicles). These are able to adapt to changes in their transport route, avoid obstacles and cope with human interaction. Autonomously controlled transport solutions are also available at TRL 9 (Technological Readiness Level 9 = actual system tested in the operational environment). At this level, research and development focuses e.g. on the improvement of sensory means, gesture-based communication, real-time communication, upcoming standards, etc., in order to further improve the performance of the elements and their usability in applications.

The picture is different for larger systems. According to Klein [142] an efficiency gap remains in the performance of large groups of autonomous elements as long as the control is truly decentralized. Despite the successful demonstration of the functionality of autonomous control in large vehicle fleets, neither the performance (i.e. average jobs per vehicle) nor the system robustness (i.e. reaction speed to disturbances) correspond to the classical, centrally controlled benchmarks. The latter in particular is noteworthy, since system robustness is generally considered to be an advantage of decentralized approaches. The performance gap can lead to an increased demand for vehicles. In contrast, other advantages such as fast system installation can still justify the decision for autonomous, decentralized system control today. Nevertheless, research should focus on minimizing this efficiency gap. This can be achieved by improved communication between vehicles, the use of virtual blackboard architectures or other approaches to broaden the basis for decentralized/local decision-making processes.

Even more complex is the cross-company linkage of the design of integrated autonomous systems, which are composed of different local substructures. This is unavoidable because logistics in its basic understanding connects material flows through different companies and production stages. Windt et al. point out that this integration can also include the integration of classic and autonomous solutions [227]. This is a key task for the research community, as it addresses both the physical and non-physical issues of inter-company flows, such as financial, security or other commercial facets.

It should be noted that a paradigm shift is already taking place, at least in large industrial applications. In recent years, large OEMs have been pushing their suppliers to install solutions with non-proprietary software. The goal is to take advantage of the data collected in the technical systems and to enable access to this data outside the specific technical component. This may be data from sensors such as cameras or laser scanners, stored on a proprietary open platform, sometimes called IoT platforms.

4.2. Virtualization by digital twins, modeling and simulation

In autonomous intralogistics systems, the technical subsystems such as AGVs and robots will make their own decisions. In addition to the technologies mentioned in Section 2.1, which essentially implement the interfaces to the environment, an internal “intelligence” is required to process the information. This task will be performed in the future by digital twins. Digital twins are a virtual representation of a real object, e.g. an AGV or a robot.

Digital twins of machines or their components already exist today to monitor or control the machines, e.g. in the context of predictive maintenance. In autonomous intralogistics systems, digital twins should additionally be enabled to interact, cooperate and make joint decisions that lead to a meaningful and performant behavior at a system level.

This leads to the necessity of a uniform modeling of digital twins. This can be based on existing product models from product design. These will be enriched with capabilities for interaction and decision making. Different digital twins, e.g. those of AGVs and those of pallets, will move in a virtual ecosystem and together plan, simulate and monitor their operation, and if necessary, optimize it.

In these virtual ecosystems, hierarchies of digital twins will be formed, comprising the levels of the goods to be transported, the load carrier (e.g. pallet), the means of transport (e.g. AGV) and the logistic infrastructure (e.g. shelf). One of the most important research tasks in the coming years will be how these digital twins organize themselves at the different levels and together form an overarching digital twin of the entire intralogistics system.

4.3. Autonomy hardware and humanoid robotics

Automated intralogistics systems today deal with the handling of standardized goods as well as standardized processes, thus ensuring efficiency. This leads to a multitude of automated special solutions. As will be shown in this article, a high degree of automation can already be achieved at the level of individual basic functions. Here the interfaces between the basic functions are the challenges. To achieve fully automated intralogistics systems, robots for handling processes are therefore becoming increasingly important. In the future, more flexible automated systems are to be used in a variety of ways – in terms of performance and location. The future does not belong to specialized robots that can only be used in very limited areas of activity, but rather to multifunctional robots that are able to learn and adapt to the tasks and the respective cooperation partners. While a suitable, delimited environment such as a robotic cell could have been created to ensure the performance of a robot acting alone, the robot of the future must be able to adapt to the environment. In order to be able to work hand in hand with humans, development will focus on multifunctional humanoid robots. Equipped with artificial intelligence, they not only move in a similar way to their human counterparts, but also learn on a daily basis by working together with humans. In accordance with this new form of joint learning in the real process, a symbiosis will take place in which humans and robots contribute their respective strengths and thus form a highly efficient team. As soon as the same robot then works together with another human, the robot adapts to the characteristics and strengths of its partner by compensating for its weaknesses. This means that at the symbiotic workstation, constant work performance is achieved, regardless of which employee is responsible. The robots of the future will therefore be humanoid, adaptable and highly flexible in terms of purpose and location. Today, flexible employees are used as jumpers in production, while in the future the robot or AGV will be flexibly deployed at different locations in the factory or on the company premises. If necessary, the robot will exchange its actuators for different handling requirements. One might be tempted to say that our production lines are standardized, that uniform loading equipment is used and therefore no great flexibility is required. However, if you take the example of dismantling larger machines such as a washing machine, automated dismantling is neither possible nor economically feasible today. Dismantling only becomes lucrative at high quantities. However, economies of scale can only be achieved by dismantling different devices from different manufacturers. Therefore, automated handling and dismantling requires a maximum of flexibility. A task for humanoid robots.

4.4. AI, data mining and deep learning

The degree of automation can also be further increased with increasing computing power, for example by using algorithms from artificial intelligence (AI). By using AI, information is fed back into the system. Since it is a learning system, it can adapt its own behavior based on the experience gained. For example, the forklift truck of tomorrow can then decide by itself in which sequence orders are processed [228]. The effectiveness of the AI cannot yet be estimated exactly, although practical applications already show great potential today [229].

In data acquisition, data mining methods and deep-learning algorithms can be used to further increase the level of automation [230]. It is necessary to identify which information is relevant for each specific logistics task. For example, robot arms can evaluate their performance and adapt their future movements [231] or data mining methods can identify patterns from marker evaluation [232]. Deep-learning algorithms can adjust the steering angle of AGVs to achieve virtual path navigation and personal protection [233]. The overriding goal is to transfer the research results into practice and thus to create intelligent logistics systems. Making human knowledge usable for industrial, automated problem solving is the key to future systems.

In order to further increase the use of data, the existing wealth of experience of a company can be made available with the help of an expert system and thus, for example, provide structured support to an employee in Development [234]. For example, the layout for AGV systems can be generated automatically [235].

4.5. Human-machine interface

Although AGVs are becoming increasingly intelligent and independent, they will not be able to take over all human tasks in the near future. For this reason, man and machine will continue to work together in production and logistics environments. Efficient human-machine cooperation depends largely on HMI. The acceptance of an HMI is highest in the form of speech and gestures, as this form has already proven to be more intuitive than others. This shows the great importance of further research in this field.

In recent years, two main topics related to HMI have been discussed in the literature. On the one hand, the type of interaction is being investigated and new ways of communication developed. Secondly, the organization of interaction is investigated and new principles are proposed. While the most common type of interface is still the keyboard, new forms have emerged and have become increasingly common in both everyday and professional life. Touchpads have only just replaced the traditional keyboard in many applications, and voice and gesture control is already taking over [129, 130]. Recent developments go even further, for example, by making it possible to control vehicles with portable patches that can be used like a keyboard [236]. Another option that goes beyond the use of an “interface” is the HMI sensor developed by Roh et al. [237]. They were able to create a sensor that can be applied directly to the human skin, and detect facial expressions and eye movements, for example. By automatically analyzing the sensor data of these movements, machines can be controlled with less effort than with a separate input device. In addition to the technical developments, the organization of the HMI must also be taken into account in the future. For this reason, Pacaux-Lemoine et al. [238] have established interaction principles that support a more human-centric approach. In their work they show how performance and user acceptance can be improved by moving from a technology-centered to a human-centered system design. Another approach to improving HMI is presented by Washburn et al. [239]. In this recent work they investigated the possibilities of using so-called predictive synchronization to achieve a higher degree of synchronization between man and machine. This is achieved by implementing a feedback delay, which was originally observed in physical systems, but also in interaction processes between humans.

Despite the technical challenges associated with HMI, research is needed on the organization of interaction, since the next level for a future-oriented human-machine relationship is “cooperation” rather than just “interaction” [240]. Therefore, mutual understanding and trust in each other‘s behavior is essential [241, 242]. Consequently, research must understand cognitive processes in humans in order to improve their trust in the technical systems with which they have to cooperate. For example, intelligent system design that leads to an increase in perceived transparency can help to improve trust [243].

4.6. Limits, future challenges and socio-technical aspects

To achieve maximum productivity, we must overcome several limitations and constraints at the technical and societal level, such as the availability of raw materials for batteries, the capacities of batteries, the capacities of wireless communication networks and the differing behaviors of man and machine. A good part of these challenges will be solved by continuous development within intralogistics. For example, more efficient processes will lead to less use of resources in terms of material and energy consumption. Once again, it is clear that it is not only a question of developing new technologies, but above all of forming technology and process into a well-functioning unit. This is the case regardless of whether one considers fully automated or manual scenarios.

With all the developments towards autonomous systems in intralogistics, however, the question arises as to whether in all cases and applications, the highest degree of automation is also the optimum result or whether lower levels might not sometimes constitute the better solution.

At least in the coming years, the challenge for intralogistics systems will be to achieve the most productive and efficient systems possible, involving people, autonomous components and conventional automated machines. In order to achieve this, intensive research is still needed into the different behavior of man and machine, optimal areas and applications must be defined and the best possible exchange of information between all those involved in the system must be ensured. The desired degree of automation can vary freely within the overall system or between the system components. However, man must be an integral part of this Industry 4.0 world.

Another aspect that must be taken into account is the future significance of human work in social systems and in society. Human work not only serves to earn money and secure personal prosperity or existence, but also defines social status. According to this understanding, human work is not arbitrarily substitutable. These socio-economic aspects must also be responsibly integrated into a discussion on future research and will once again confirm that technological change must always be researched jointly on an interdisciplinary basis between the technical sciences, work organization, business administration and many other disciplines.

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