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Offloading Functions of Autonomous Mobile Robots to a Cloud

Auslagerbarkeit von Funktionen autonomer mobiler Roboter in eine Cloud

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Autonomous Mobile Robots (AMR) are used in intralogistics to automate internal transport processes. In addition to the increasing number of robots in the system, the demands on the performance of AMR are increasing due to more complex use cases. At the same time, cloud computing is a key technology for handling data- and compute-intensive processes on demand. This work explores the possibility of offloading AMR functions to the cloud and taking advantage of both technologies. To this end, AMR functions are defined and differentiated in a flowchart. After identifying offloading-relevant criteria, the potential of offloading these functions to the cloud is examined using the Analytical Hierarchy Process method. The results show that cross-AMR functions such as traffic control, task assignment, task planning, mapping and path planning have a high potential for offloading to the cloud. On the other hand, AMR functions that require a fast and reliable response time or are safety relevant should be executed on the AMR itself. However, these results underscore that AMRs and the cloud can be combined to great advantage.

[Keywords: Offloading, Decision making, Analytical Hierarchy Process, Autonomous Mobile Robots, Cloud-Edge]

Autonome mobile Roboter (AMR) werden in der Intralogistik zur Automatisierung innerbetrieblicher Transportprozesse eingesetzt. Neben der steigenden Anzahl von Robotern im System steigen auch die Anforderungen an die Leistungsfähigkeit von AMR durch komplexere Anwendungsfälle. Gleichzeitig ist Cloud Computing eine Schlüsseltechnologie, um daten- und rechenintensive Prozesse bedarfsgerecht zu verarbeiten. Dieser Beitrag untersucht die Möglichkeit, AMR-Funktionen in die Cloud auszulagern und die Vorteile beider Technologien zu nutzen. Dazu werden AMR-Funktionen definiert und in einem Ablaufdiagramm voneinander abgegrenzt. Nach der Identifikation auslagerungsrelevanter Kriterien wird das Potenzial der Auslagerung dieser Funktionen in die Cloud mit Hilfe der Methode des analytischen Hierarchieprozesses untersucht. Die Ergebnisse zeigen, dass insbesondere AMR-übergreifende Funktionen wie z. B. Verkehrssteuerung, Fahrzeugdisposition, Transportauftragsverwaltung, Kartierung und Pfadplanung ein hohes Potenzial für die Auslagerung in die Cloud aufweisen. AMR-Funktionen, die eine schnelle und zuverlässige Antwortzeit erfordern oder sicherheitsrelevant sind, sollten hingegen auf dem AMR selbst ausgeführt werden. Diese Ergebnisse unterstreichen jedoch, dass AMR und Cloud vorteilhaft kombiniert werden können.

[Schlüsselwörter: Auslagerung, Entscheidungsfindung, analytischer Hierarchieprozess, autonome mobile Roboter, Cloud-Edge]

1 INTRODUCTION

The fourth industrial revolution demands extensive changes in production and logistics. The principal drivers of this transformation are the growing networking and integration of intelligent systems, the digitalization of processes and the utilization of innovative technologies [1, 2]. In the field of intralogistics, which focuses on the internal material and information flows [3], autonomous mobile robots (AMR) represent one of the key technologies [4]. The use of AMRs offers great potential for the optimization of intralogistics processes. The robots are capable of autonomously transporting materials and products, monitoring stock levels, and executing production steps [5].

The increasing digitalization and networking of production and logistics systems requires not only automation solutions for material transports, but also the use of powerful information and communication technologies [6]. Cloud Computing plays a pivotal role in this context, as it allows companies to provide demand-driven and scalable computing resources and IT-infrastructure [7]. The interconnection of industrial systems, machines, and products with a cloud-based infrastructure enables the real-time recording, processing, and analysis of data. This facilitates a

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wide range of possibilities for the improvement of production and logistics processes, including data-driven decision-making and demand-driven resource allocation [8].

Comprehensive research already exists on both AMRs and cloud technologies. However, a synthesis of these two domains that investigates a strength-oriented interaction between AMRs and the cloud by integrating their mutual benefits has yet to be adequately explored. In the light of these findings, this article examines the potential for offloading the functions currently performed on board the AMRs to a cloud. To this end, the functions involved in the execution of AMR processes are broken down into differentiated and assessable function modules. Then, criteria are derived that are essential when offloading AMR functions to a cloud. Once the basis for evaluation has been established, the potential of offloading the AMR functions is determined by carrying out the Analytic Hierarchy Process (AHP) method. The analysis and classification of the technical feasibility of the implementation complete the process.

2 FUNDAMENTALS

2.1 AUTONOMOUS MOBILE ROBOTS

AMR have become the symbol of the automation of transport processes [4]. Since AMRs have evolved from automated guided vehicles (AGV), it is necessary to first examine the concept of classic AGVs to then gain an accurate understanding of AMRs [9]. AGV systems comprise one or more vehicles in combination with a high-level master control [10]. The master control serves an overarching function, managing the entire system to complete transport tasks. Advances in sensor technology and software have resulted in the continuous development of AGV functions. This has led to an increased system intelligence, as perceived by the users. The intelligence is most evident in the increased degrees of freedom in driving maneuvers and the simplified integration into operational processes [9, 11].

In this context the term “AMR” has emerged. The Robotic Industries Association provides a high-level definition of the distinction between AGVs and AMRs based on the navigation methods employed [12]. AGVs are guided by tracks, which range from physical guidelines to virtual, software-based tracks that are stored within a predefined digital map. In contrast, AMRs navigate freely through the workspace based on a self-recorded map and additional sensor information. The AGV Technical Committee of the “Verein Deutscher Ingenieure” (VDI) has further expanded the autonomy of a transport system in a guideline, defining an automatic and autonomous version for various functions [11]. Autonomous functions include, for example, the ability to navigate approved areas without a specified lane, while avoiding obstacles and responding to the surroundings based on object recognition and classification. An approach to autonomy can also be found in Fottner et al. [5], who adapted the levels of autonomous driving from cars to intralogistics systems. The systems are distinguished according to three criteria: the environment in which they operate, the location of decision-making, and the interaction of the system elements. Consequently, autonomous systems are deployed in highly complex and dynamic environments and utilize decentralized decision-making. Moreover, a high level of interaction between its system elements is characteristic of autonomous systems.

For the understanding of this work, it is essential to recognize the execution of transport processes in intralogistics as the primary objective of AMRs. To fulfill this objective, the system must perform a range of functions. These functions can be executed in the robots themselves, in a centralized control system, in a cloud, or in a combination of these three.

2.2 CLOUD/EDGE COMPUTING

In recent years, there has been a notable shift in the activities of companies towards digital spaces demanding high computing power and storage capacities, requiring the content being offloaded [13]. One solution to this problem is cloud computing, which involves the use of flexible, high-performance hardware and software infrastructure that users can access as required. The cloud computing architecture is centralized. A significant disadvantage of this approach is the potentially high latency experienced by users at the network edge (e.g. AMRs on the shop floor) when communicating with the cloud [14]. In practice, cloud structures are typically supplied by large providers (e.g. Microsoft, Amazon, Google), which raises concerns about the security of company data in the cloud.

An extension of cloud computing is decentralized and distributed edge computing, in which fewer calculations are performed in the cloud and instead are carried out closer to the data source on the shop floor [14]. By utilizing resources at the edge of the network, the latency and bandwidth of the system can be improved. Therefore, edge computing is the antithesis of cloud computing in terms of latency, bandwidth, storage capacity and computing power.

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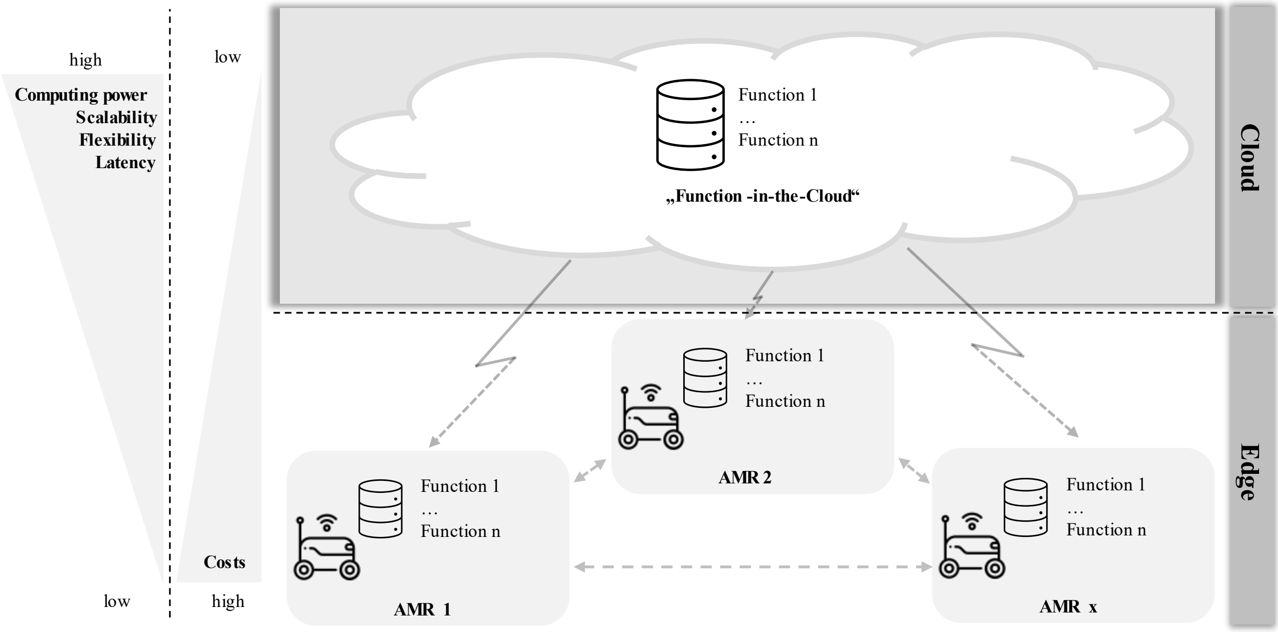

Figure 1. Cloud-edge network for AMR (based on [15])

Regarding the content of this work, the AMRs are situated at the edge of the network and possess their own computing power through onboard processors (see figure 1). The combination of edge computing with a cloud appears to be a promising design approach for the optimal allocation and provision of computing power and functions in the overall system, as the advantages of both paradigms should be combined as far as possible.

3 METHODOLOGY

3.1 AMR REFERENCE PROCESS AND FLOWCHART

To start, the basis for the evaluation must be established. This is achieved by first defining a reference process for intralogistics transports (see figure 2) and then deriving the AMR functions involved in the process execution.

The execution of transport processes is one of the most widespread activities in intralogistics, representing the core task of AMRs and the focal point of the proposed methodology. The reference process is based on the exemplary sequence of transport processes defined and is expanded to include AMR-specific aspects [16]. The transport process is initiated with the provision of information regarding the subsequent transport order via the IT system. Until then, the AMR remains in a waiting position. If the AMR is not directly at the source of the transport order, a trip must first be made to the corresponding source, which is classified as an empty trip. The third step in the reference process is to pick up the transport unit at the source, which is described by the load pick-up process step. In contrast to the empty run, the distance traveled with the transport unit from the source to the sink is referred to as a load run. Ultimately, the transport unit is transferred to the sink in the form of a load delivery and the process can be restarted with the provision of information regarding the subsequent transport order. In bundled transport processes (e.g. tugger trains), multiple transport units are conveyed by the AMR simultaneously. This results in the concurrent execution of individual operations rather than their sequential execution. If the battery charge level is insufficient for the subsequent transport order, an empty run to a charging station is initiated. Once the AMR has reached an adequate charge level, it is able to accept the subsequent transport order.

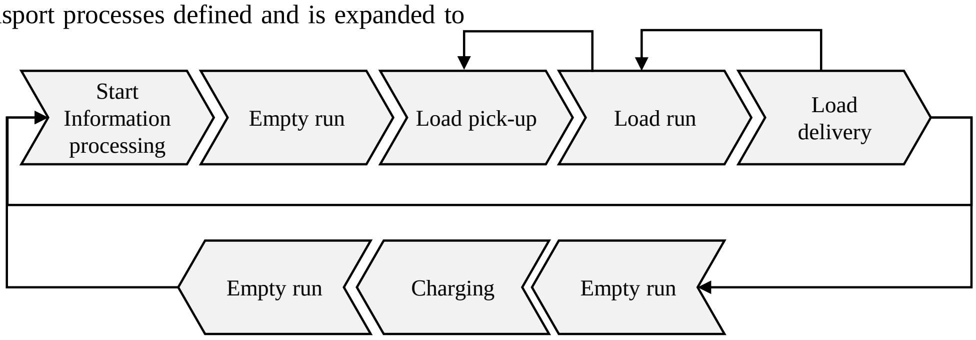

Figure 2. AMR reference process (based on [16])

The fulfillment of the transport task and the subsequent reference process are dependent on a multitude of software and hardware components. These components encompass both cross-AMR and AMR-internal functions. The functions serve as the basis for the evaluation of offloading decisions. A generic flowchart is created to better understand the differentiation between the functions (see figure 3). It should be noted that the need to implement a function in an AMR depends on the respective use case. As existing function descriptions for AMRs do not adequately reflect the scope of this paper, these have been supplemented by literature research and expert interviews to create a complete generic flowchart [17–20]. A total of 13 functions were identified and a detailed description of the functions can be found in figure 8 in the appendix:

- Task planning [17]
- Task allocation [21, 22]
- Localization [23–25]
- Mapping [26, 27]
- Traffic control [28–30]
- Path planning [31–33]
- Obstacle avoidance [34–37]
- Positioning [38, 39]
- Trajectory planning [40, 41]
- Trajectory tracking [42, 43]
- Safety functions [44]
- Energy management [45, 46]
- Service functions [17]

The planning and control processes of an AMR system are initiated upon the submission of a new transport order by a client. Subsequently, the order is accepted and processed from an administrative standpoint. In the initial function of task planning (1), sequences of individual driving tasks are generated from the transport order. The driving tasks correspond to the process steps of the reference process in figure 2. The transport orders are then assigned to the most suitable AMR in the task allocation function (2). The assignment is typically made by estimating the shortest transport time or distance. The transport order is subjected to further processing in the function of path planning (6). This process determines the most optimal global path for the selected AMR on the shop floor. To this end, the current position of the robot is determined in real time in the localization (4) function. Moreover, the map of the shop floor is updated continuously in function of mapping (3). To prevent deadlocks, the current traffic status of all AMRs in operation is prepared and processed in the traffic control (5).

Considering the global path as well as dynamic changes in the environment, the motion of the robot for the present time frame is planned. In the obstacle avoidance function (7), dynamic obstacles are detected and classified. Furthermore, precise target positions are identified in positioning (8) through the analysis of image or laser data, thereby enabling the robot to approach load carriers or charging stations with high accuracy. In the trajectory planning function (9), the obstacles and target positions are used to determine the local trajectory as a function of the robot's velocity and acceleration.

The actuators are linked to the control system of the robot via motion control. In trajectory tracking (10), the determined trajectory is converted into functions of the required torques for the actuators. The safety functions (11) are used to detect individuals and objects within the safety-critical zone in front of the AMR and to initiate the braking process in the event of an emergency. The required energy is provided by the energy management function (12), which also optimizes the robot's energy consumption. Applications designed to provide user support, such as visualizations or status messages displayed on the user interface, are grouped together as service functions (13).

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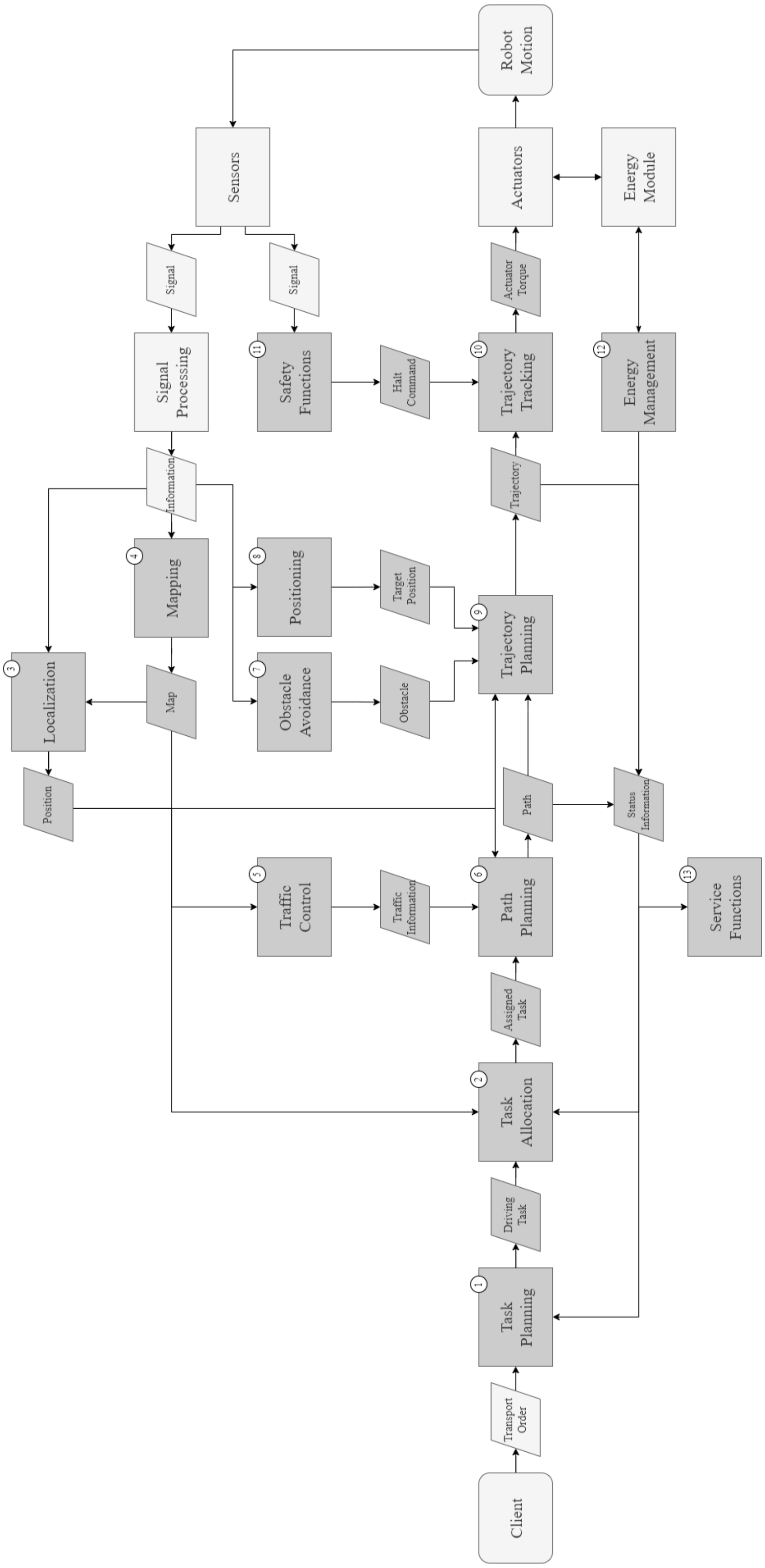

Figure 3. *AMR flow chart*

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The flow chart is completed with the addition of information resulting from the execution of a function, which simultaneously serves as input for a downstream function. Hardware components (e.g., actuators) are incorporated into the overall picture, yet they are not included in the evaluation of the offloading. All perception tasks are included in their superordinate functions (e.g. object detection as part of obstacle avoidance) as their scope depends heavily on the respective objective.

3.2 ANALYTICAL HIERARCHY PROCESS

The AHP method is a multi-criteria decision-making (MCDM) approach used to facilitate the decision-making of subjective, generally non-quantifiable and intuitive decisions [47]. The hierarchy lies in the decomposition of the decision problem into several levels (see figure 4). At the top level, the decision problem is defined. It is then broken down into evaluation criteria and decision alternatives at the subsequent levels. Another central feature of the AHP method is the use of pairwise comparisons, which ensure an objective weighting of the decision criteria and alternatives. In a pairwise comparison, two criteria are evaluated against each other in terms of their relative importance [48]. A weighting of criteria can also be used in the related weighted sum method. However, in contrast to the weighted sum method, the AHP compares the decision alternatives directly with each other and does not evaluate them in isolation, as the pairwise comparison is also applied to the alternatives [49].

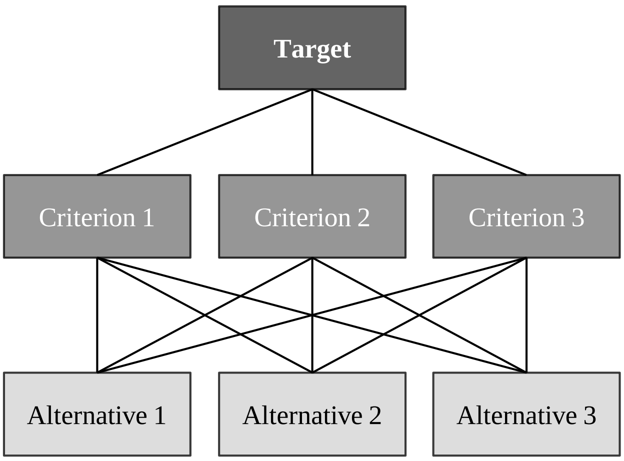

Figure 4. Basic framework AHP (based on [48])

The assessment is typically based on expert interviews. These are particularly suitable when little or no historical data is available, and a purely quantitative assessment is not feasible [50]. Haag [51] notes that innovations with significant potential to increase value are more likely to be prioritized in qualitative assessments than in quantitative ones.

The criteria n and the alternatives m are used to explain the mathematical basis of the AHP method. At each hierarchy level, the pairwise comparisons result in an evaluation with independent weightings. The result of the method is the AHP score, which is calculated by multiplying the weights of the alternatives by the superordinate weights of the criteria.

The linguistic assessments are converted into numerical values, thereby enabling calculations within the method. In accordance with Saaty [47], the linguistic ratings ranging from "equally important" to "significantly more important" are assigned values from one to five, while the opposite ratings are given the reciprocal values. To calculate the weights, pairs of the n elements are compared with each other at the hierarchy level of the criteria. The preference of criterion i over criterion j is indicated by a_{ij}. These preferences are entered in the n x n matrix A. The diagonal of the matrix is comprised of ones, as the criteria are evaluated against themselves. The numbers with their corresponding reciprocal values are always mirrored to the left and right of the diagonal. Therefore, the following applies:

$$a_{ji} = \frac{1}{a_{ij}} \quad i, j \epsilon \{1,2,..,n\} \tag{1}$$

To obtain the weighting of the criteria, the principal eigenvector of the matrix A is determined and normalized. The resulting weighting vector v contains the global weights v_i.

$$v = (v_1, v_2, \dots, v_n)^T \tag{2}$$

The calculation of the alternatives m is carried out for each criterion i and follows the same principle. After translating the linguistic evaluations into numbers, the m x m matrix B^i with the preferences b_{kl}^i of alternative k over alternative l is obtained. The principal eigenvector w^i is determined from the matrix, which contains the relative weights w_k^i of the alternatives after normalization.

$$w^i = \{w_1^i, w_2^i, \dots, w_m^i\} \quad i \in \{1,2, \dots n\} \tag{3}$$

The final AHP score of the alternative k is determined by multiplying the weight of the alternatives w_k^i by the global weights of the criteria v^i:

$$AHP\ Score_k = \sum_{i=1}^{n} w_k^i * v_i \tag{4}$$

$$i \in \{1,2, \dots, n\}, k \in \{1,2, \dots, m\}$$

4 EVALUATION OF THE OFFLOADING OF AMR-FUNCTIONS

4.1 ADAPTED AHP-DESIGN AND EXPERT PANEL

At the first hierarchy level of the AHP method for evaluating offloading capability, the decision problem is formulated as follows: Is the AMR function better implemented on board the AMR or in a cloud? The remaining levels can be derived directly from the formulation of the decision problem. The second hierarchy level contains criteria that are pivotal in the decision to offload, while the third hierarchy level consists of the two alternatives for implementation, namely on board the AMR and in the cloud. The evaluation is individually conducted for each of the AMR functions. Each function is evaluated in accordance with the specified criteria. Figure 5 shows the hierarchical structure and the linking of the hierarchies.

On the one hand, the established evaluation criteria are based on the general advantages of cloud computing [52, 53] (e.g. cost advantage, scalability). On the other hand, a literature review on cloud robotics [52, 54–59] (e.g. processing time, energy consumption, quality of results) and AMR use cases [17] (e.g. safety) resulted in additional criteria. For the sake of clarity, the seven evaluation criteria are assigned to three categories: economic, technical, and strategic. The evaluation criterion "costs" is classified under the economic criteria. The technical evaluation criteria include processing time, energy consumption, quality of results and safety. Finally, the strategic evaluation criteria consist of availability and scalability. Figure 9 in the appendix offers an overview of the evaluation criteria, including the definitions used in this study, as well as the target values for each criterion.

The AHP method was conducted via an expert survey. To provide targeted responses, scientific (five experts) and industry experts in the fields of logistics and IT were interviewed. This approach ensures the integration of both theoretical and practical perspectives into the AHP method. The industry experts include experienced planners and users of AMR and cloud projects (six experts) as well as AMR manufacturers (five experts). As a result, the interdisciplinary nature of the AMR cloud combination is reflected, which leads to a high and realistic informative value of the results. The AHP method was conducted by a sample of 16 experts (n = 16).

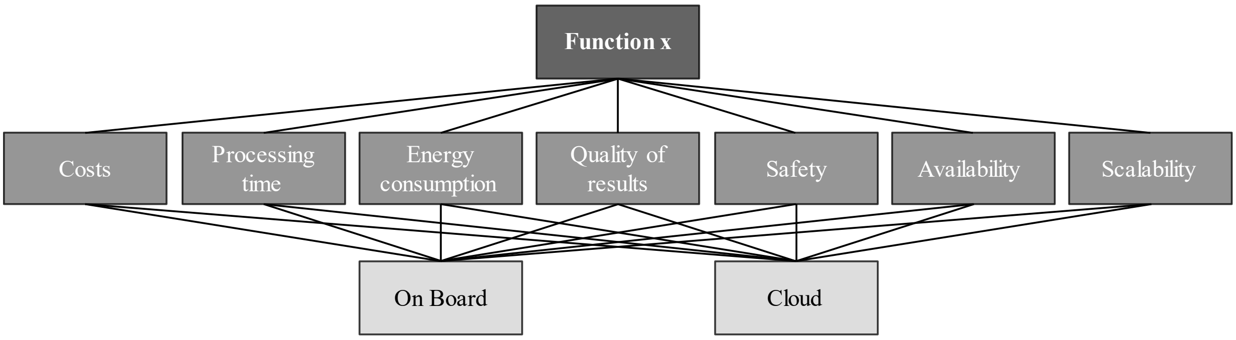

Figure 5. Adapted AHP-Design

4.2 EVALUATION OF CRITERIA

The results demonstrate that the evaluation criteria are of varying importance with respect to the decision to offload AMR functions. Table 1 illustrates the ranking and relative importance of the criteria, as determined through the pairwise comparison.

Safety and availability were identified as the most important criteria. In intralogistics, AMRs are often deployed in shared workspaces with personnel and manually guided forklifts and tugger trains. While safety is essential in all AMR systems, it is particularly significant in hybrid work environments. The relevance of availability can be traced back to the use of cloud computing. In this case, the connection to the cloud represents a bottleneck. In the event of a connection failure, functions can no longer be executed properly. The duration and type of function affected will determine whether the AMR is brought to a standstill. In small systems, faults can still be rectified by performing the transport task manually and keeping job-hoppers available. In larger systems, this emergency strategy is not viable. A loss of connection to the cloud or a cloud failure can result in costly disruptions.

Table 1. Ranking and weights of evaluation criteria

Ranking (according to weight)	**Value**
1. Safety	0.31
2. Availability	0.22
3. Quality of results	0.13
4. Costs	0.11
5. Scalability	0.10
6. Processing time	0.08
7. Energy consumption	0.04

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The quality of results of a function is of great importance, regardless of where it is performed. Furthermore, any decision to offload must be made with a clear understanding of associated costs. It is noteworthy that in the efficiency-driven environment of production and logistics, this criterion is not given greater consideration. A similar observation can be made for the criteria of scalability, processing time and energy consumption, as a substantial body of research [52, 60, 61] has been conducted on these criteria in recent years.

4.3 Evaluation of offloading potential of AMR-functions

The application of the AHP method enables the determination of whether each AMR function should be offloaded to the cloud. Given that only two alternatives are being compared, the mean of the achievable minimum and maximum value of the AHP score represents the threshold between the alternatives. If the AHP score exceeds 0.5, the AMR function should be offloaded. If the AHP score is below or equal to 0.5, the function should be processed on board the AMR. The results of the evaluation are analyzed in two stages. Initially, the YES or NO results regarding each function are presented (see figure 6). These are obtained by adding up all the benefit values of the evaluation criteria for each function. Subsequently, the interim values of the evaluation prior to determining the final AHP scores are considered. This allows for a more nuanced understanding of the decision process.

Result (n = 16)	1. Task Planning	2. Task Allocation	3. Localization	4. Mapping	5. Traffic Control	6. Path Planning	7. Obstacle Avoidance	8. Positioning	9. Trajectory Planning	10. TrajectoryTracking	11. Safety Functions	12. Energy Management	13. Service Functions
Costs	0,08	0,08	0,05	0,06	0,08	0,07	0,05	0,05	0,06	0,06	0,05	0,06	0,07
Processing Time	0,06	0,06	0,03	0,05	0,06	0,05	0,02	0,03	0,03	0,02	0,02	0,04	0,05
Energy Consumption	0,03	0,03	0,02	0,03	0,03	0,03	0,02	0,02	0,02	0,02	0,02	0,02	0,02
Quality of Results	0,10	0,10	0,07	0,08	0,10	0,09	0,06	0,06	0,07	0,05	0,04	0,08	0,09
Safety	0,16	0,17	0,13	0,16	0,17	0,14	0,09	0,11	0,09	0,07	0,07	0,14	0,16
Availability	0,13	0,13	0,10	0,10	0,13	0,11	0,07	0,08	0,08	0,07	0,05	0,10	0,11
Scalability	0,09	0,08	0,07	0,07	0,08	0,07	0,06	0,06	0,06	0,06	0,05	0,07	0,07
AHP-Score	0,63	0,65	0,46	0,54	0,65	0,55	0,38	0,40	0,43	0,34	0,29	0,50	0,58
Offloading	**YES**	**YES**	**NO**	**YES**	**YES**	**YES**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**YES**

Figure 6. Yes or No results of offloading

As illustrated in figure 6, the execution of cross-AMR and administrative control functions is more optimal in a cloud environment. The AMR functions of traffic control (0.65), task allocation (0.65) and task planning (0.63) have been assigned the highest AHP score. This finding aligns with the required work steps associated with the functions and the cloud-related benefits identified in the literature review. In an environment with an overview of the entire AMR fleet, task planning and allocation can be carried out optimally. This ensures that the most suitable AMR is selected for a given order. Moreover, the deployment of AMRs with the capacity to receive data from the entire system, rather than solely from their own sensors, has the potential to enhance the efficiency of traffic control. The use of a global map generated by mapping (0.54) in the cloud and path planning (0.55) also contributes to this aspect. Furthermore, service functions (0.58) such as the provision of AMR status data, information on successful and unsuccessful processing of transport orders, or updates for the AMR fleet can be more efficiently managed in the cloud. The functions that are assessed as beneficial for offloading are, in the context of conventional AGV systems, typically allocated to the master control. The offloading potential is further enhanced when heterogeneous AMR fleets are considered, in addition to homogenous ones, as the manufacturers own master control system can be replaced by a central, overarching control system. This is the premise of the VDA5050 [62] guideline, which is intended to enable manufacturer-independent master control. The first industrial applications have already been implemented in the domain of fleet control. Exemplary solutions are offered by Synaos or idealworks.

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Normalized Evaluation (n = 16)	Weight	1. Task Planning	2. Task Allocation	3. Localization	4. Mapping	5. Traffic Control	6. Path Planning	7. Obstacle Avoidance	8. Positioning	9. Trajectory Planning	10. TrajectoryTracking	11. Safety Functions	12. Energy Management	13. Service Functions
Costs	0,11	0,74	0,71	0,46	0,56	0,68	0,58	0,47	0,41	0,54	0,48	0,41	0,53	0,61
Processing Time	0,08	0,67	0,68	0,32	0,61	0,75	0,61	0,24	0,33	0,31	0,27	0,19	0,45	0,61
Energy Consumption	0,04	0,65	0,69	0,54	0,59	0,63	0,63	0,56	0,58	0,55	0,45	0,51	0,54	0,55
Quality of Results	0,13	0,76	0,77	0,54	0,63	0,78	0,73	0,49	0,45	0,58	0,39	0,30	0,61	0,68
Safety	0,31	0,51	0,55	0,41	0,50	0,55	0,44	0,30	0,34	0,31	0,24	0,22	0,45	0,52
Availability	0,22	0,57	0,58	0,44	0,46	0,57	0,48	0,32	0,36	0,38	0,30	0,24	0,44	0,52
Scalability	0,10	0,82	0,80	0,65	0,66	0,80	0,70	0,57	0,54	0,62	0,54	0,50	0,63	0,71

Figure 7. Evaluation in detail

In contrast, the results indicate that functions which require fast processing and response times should not be offloaded to a cloud. These include safety functions (0.29), trajectory tracking (0.34), obstacle avoidance (0.38), positioning (0.40), localization (0.46), and energy management (0.50). This observation is also consistent with the findings of the literature research. Delayed responses in these functions would potentially impair road safety and hinder the efficient and rapid execution of AMR movements.

Figure 7 presents the results of the evaluation in detail. The evaluations regarding safety and availability are especially influential, given the greater weight accorded to these criteria. Conversely, these two criteria are currently pivotal in determining whether to offload AMR functions to the cloud. In this regard, the current range of wireless technology options may present a challenge. It is therefore essential to consider the technical feasibility of offloading in addition to the qualitative evaluation.

4.4 Technical Feasibility

The evaluation of offloading AMR functions cannot be separated from the technical feasibility of implementation. In this context, two requirements must be emphasized. Firstly, the cloud service must be equipped with sufficient computing power to perform the required function. Secondly, the data required must be transferred from the AMR to the cloud servers and vice versa. Both processes must be completed within a certain period so that the robot can adequately react to the conditions in its working environment. The required response time varies from minutes (e.g. task planning) to milliseconds (e.g. safety functions), depending on the function. The processing time, which results from the computing time and the transfer time between the cloud and the edge, must be less than the response time required.

The computing time is not a significant concern, as the computing power of a cloud can be adjusted as needed. The primary challenge of the technical implementation of cloud-based AMR systems is the transfer time. This is mainly determined by the attributes of the communication network connecting the AMR and the cloud. In this context, it can be stated that the greater the bandwidth and the lower the latency, the faster data packets can be transmitted. It is essential to ensure that the data volume can be transferred between the AMR and the cloud by providing a sufficiently large bandwidth. The estimation of the latency results from the sum of the transmission time T_x, propagation delay T_p and buffer time T_b [63]:

$$Latency = T_x + T_p + T_b \tag{5}$$

It is important to highlight that the latency times calculated with the estimate differ significantly from the empirical values obtained from industrial implementations. The reason for this discrepancy is the inherent complexity of real cloud server architectures [64]. These contain numerous intermediate stations and require various information protocols, resulting in significant delays that cannot be calculated [65, 66]. Furthermore, the latency times of the servers are dependent on the cloud providers, who often fail to provide expected delay times. In conclusion, although latencies can be estimated, reliable values can only be determined through testing on real cloud-based AMR systems.

Redundancy and caching can be a solution to minimize the impact of latency and bandwidth issues. Specific examples include geo-redundancy and zone-redundancy [67, 68]. The technical feasibility study also shows that a hybrid design of scopes in the cloud and scopes at the edge makes sense [69].

5 Conclusion

This study has investigated the potential of offloading AMR functions to a cloud. Based on the development of a flowchart, which includes a standardized AMR transport process and a classification of the functions involved in the execution, criteria for the offloading decision were identified. Based on this assessment, the AMR functions were evaluated regarding their offloading potential using the AHP method. Finally, the technical feasibility of offloading was assessed.

The application of the AHP method has demonstrated that AMRs can be managed more effectively when integrated into a cloud-based system. The most beneficial functions for offloading are those related to cross-AMR management and control, namely traffic control, task allocation, task planning, mapping, and path planning. In contrast, experts determined that AMR functions, which require a rapid and dependable response time, are best performed on board the AMR. In this regard, the primary consideration is the safety relevance of functions such as safety itself and localization. The classification of safety as the most important evaluation criterion for offloading underlines this aspect. From a technical standpoint, the offloading of AMR functions to the cloud necessitates the availability of a wireless connection with sufficient bandwidth and low latency. The resulting requirements vary depending on the specific AMR function. In conclusion, it can be stated that bandwidth is the less critical key figure due to new possibilities, such as the 5G mobile communications standard. Latency, on the other hand, is a more critical factor in the offloading of AMR functions to the cloud. This is due to the distance that must be traversed from the AMR to the cloud and, additionally, the latency time of the cloud itself, which is often operated externally.

By modeling the AMR functions in the form of function blocks, which are displayed in a flowchart, the entire AMR process can be mapped in detail. This enables even those without prior experience to conduct in-depth analysis and optimization of robot performance. Moreover, the potential benefits and applications of integrating AMRs with cloud computing were systematically explored in the context of initial industrial implementations. It has been demonstrated that specific AMR functions that are computationally or memory-intensive can be performed with greater efficiency in a cloud environment. The potential is particularly evident in the context of larger AMR fleets. As the number of mobile robots in a system increases, the importance of central data processing and robot coordination in the cloud also rises. This allows for more efficient use of robot resources, as the AMRs only require the necessary performance components. This can also result in cost savings. AMR manufacturer independence is an important requirement for large users. By standardizing the interfaces (e.g. VDA5050) between AMR and cloud, cross-manufacturer integration can be made possible, thereby increasing the flexibility and scalability of the overall system.

The practical implementation of cloud-based AMR systems represents a logical progression regarding this project, particularly considering the preliminary assessment of their technical feasibility. The need for further research is therefore primarily concerned with the practical validation and proof of offloading. Furthermore, actual latency values can be quantified, and the impact of offloading on AMR operations can be more fully understood and analyzed. Nevertheless, this study offers valuable insights into the prioritization of functions for offloading in an experimental setting, which warrants further investigation.

In summary, combining AMRs with a cloud offers significant advantages in terms of function distribution, scalability, and vendor independence. This approach is a promising way to further increase the performance of AMRs.

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APPENDIX

Category	Order Management (h - min)		Navigation (min - s)			
Function	1 Task Planning	2 Task Allocation	3 Localization	4 Mapping	5 Traffic Control	6 Path Planning
Input	Transport Order	Driving Task, Map, AMR-Positions	Sensor Information, Map	Sensor Information	Map, AMR-Locations	Assigned Driving Task, Map, AMR-Location, Traffic Information
Output	Driving Task	Assigned Driving Task	AMR-Location	Map	Traffic Information	Path
Description	Receives incoming Transport Orders and converts them into specific Driving Tasks	Allocates the Driving Tasks to the most suitable AMR	Determines the location of the AMR on the Map using Sensor Information	Creates a Map of the shop floor using Sensor Information	Collects Traffic Information to avoid deadlocks	Determines the most suitable Path to fulfill the Driving Tasks (route from source to sink)

Category	Motion Planning (s - ms)			Motion Control (ms - µs)		Other	
Function	7 Obstacle Avoidance	8 Positioning	9 Trajectory Planning	10 Trajectory Tracking	11 Safety Functions	12 Energy Management	13 Service Functions
Input	Sensor Information	Sensor Information	Path, Map, AMR-Location, Obstacle Position, Target Position	Trajectory	Sensor Signal	Charge Level	Status Information
Output	Obstacle Position	Target Position	Trajectory	Actuator Torque	Halt Command	Status Information	N/A
Description	Detects Obstacles and determines their relative Position using Sensor Information	Recognizes the target object (e.g. undercarriage rack) and determines the desired Target Position (e.g. for load handling)	Calculates the required Trajectory (speed, acceleration of the AMR along the Path)	Calculates the required Acturator Torque to track the trajectory	Detects persons and objects in the danger zone and initiates the braking process	Optimizes the required amount of energy and reports the status of the Charge Level	Provisions service applications (e.g. via the user interface)

Figure 8. Description of the AMR functions

Category	Criterion	Description	Better is…
Economic	Costs	The costs incurred (takes into account investment and operating costs)	lower costs
Technical	Processing Time	The duration from the triggering of the function to its completion (takes into account the duration of the data transfer (network) and the duration of the calculation (onboard CPU/cloud); does NOT take into account the physical execution by the robot)	lower processing time
	Energy Consumption	The power consumption of the robots during operation (does NOT include the power consumption of the cloud and the network)	lower energy consumption
	Quality of Results	The achievable quality level of the calculated results (e.g. for path planning: The quality of the selected path (shortest distance, adapted to the traffic situation, etc.)	higher quality of results
	Safety	The achievable physical safety on the shop floor (takes into account the safety of persons and objects; does NOT take into account the data security of the cloud/databases)	higher safety
Strategic	Availability	The proportion of time during which the system is available without technical failure (takes into account all planned outages (e.g. maintenance) and unplanned outages (e.g. accidents, faults))	higher availability
	Scalability	The ability to integrate additional robots into the system (the lower the effort for the integration of new robots, the higher the scalability)	higher scalability

Figure 9. Description of the evaluation criteria