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Hierarchical And Flexible Navigation For AGVs In Autonomous Mixed Indoor And Outdoor Operation

Maximilian Zwingel[1], Lukas Baier[1,2], Andreas Blank[1] , Jörg Franke[1]
[1]*Institute for Factory Automation and Production Systems (FAPS), Friedrich-Alexander-University Erlangen-Nuremberg, Erlangen, Germany*
[2] *Technische Hochschule Ingolstadt, Germany*

Abstract

Globalized markets require a high degree of flexibility in existing production and logistics environments. Flexible intralogistics systems are one key component for enabling versatile production by ensuring material supply and providing a dynamic link between different production stages. Challenged by historically grown production layouts and the increasing need of adaptable supply routes due to new forms of workshop organization like matrix production, state-of-the art approaches for intralogistics systems based on automated guided vehicles (AGVs) are not sufficient for mixed indoor and outdoor operation. In order to enable a truly flexible operation of systems in these mixed indoor and outdoor scenarios, new solutions for navigation and planning as well as increased autonomous capabilities of AGVs need to be focused (e.g. adaptive detection of driveable regions).

In this paper, we propose an approach of hierarchical navigation utilizing a node-based representation of the production and logistics environment to allow flexible pathing and routing of AGVs. Based on inherent information of each node, autonomous capabilities of AGVs are activated according to the requirements of the area of operation. To prove reliability of the proposed hierarchical and flexible navigation, an evaluation of the approach is performed utilizing an industrial mobile system enhanced by autonomous capabilities in varying real-world cross-building scenarios.

Keywords

Autonomous Two Truck Systems; Network Based Pathing and Routing; Digitalized Production Environment

1. Introduction

Modern production concepts place high demands on the flexibility and availability of intralogistics systems as a link between general material supply and the individual production stages [1]. As a reactive supply system with high availability, automated guided vehicles (AGVs) are gaining popularity in an increasing number of application areas, [2] driven in particular by the transfer of high-performance sensors and algorithms from the field of autonomous driving [3] as well as advances in the area of free navigation without infrastructure. [4–7]

One key element that prevents the use of AGVs in production environments is the need for the intralogistics system to be operated between buildings with mixed traffic, as required by historically grown infrastructure with physically separated warehouses and shop floor buildings as shown exemplary by the Audi plant in Ingolstadt in figure 1. Indoor and outdoor areas place specific and different demands on navigation of AGVs, which result from different environmental influences, the volatility of the working environment and operational specifications. This concerns both the global level of navigation, involving the path planning between a starting point and a destination, and path execution (local level of navigation) including the sensing of and reaction to obstacles in the environment on the planned path. For indoor areas with relatively constant environmental conditions and quasi-static settings, different approaches to path planning have to be pursued than for outdoor areas with changing environmental conditions and frequent changes in scene due to mixed traffic. The situation is similar in the area of path execution, where the reliability and information content of different sensors differ significantly for indoor and outdoor scenarios, requiring efficient switching of the chosen solution for navigation.

Figure 1: Historically grown factory layout with mixed indoor and outdoor areas given by example of the AUDI factory in Ingolstadt in Germany. Hypothetical production areas (green) are separated from storage areas (blue) by outdoor paths of varying lengths (orange) (left: Orthofoto DOP80 © Bayrische Vermessungsverwaltung, CC BY 3.0 DE, right: © OpenStreetmap contributors, CC BY-SA 4.0)

To enable a holistic navigation of AGVs without losing the advantages of specific algorithms, we present a framework for hierarchical navigation using a node-based representation of the working environment. Introducing a top-level planning instance enables flexible navigation of AGVs and offers the possibility to activate required autonomous capabilities of AGVs by inherent information coding.

In the following chapter work related to navigation in mixed indoor and outdoor areas for AGVs is outlined. In the third chapter the proposed framework for hierarchical navigation utilizing a node-based representation of the working environment with inherent information encoding is presented and the control of autonomous capabilities based on inherent information is detailed. In chapter 4 the hierarchical approach for flexible navigation is exemplary implemented using an AGV in a reference scenario for evaluation purposes. Finally, an outlook on further improvements is given.

2. Related work

Research in the field of mixed indoor and outdoor navigation for AGVs has been gaining popularity lately following the increasing availability of adequate sensors and outdoor capable vehicles as well as press coverage of companies planning to utilize autonomous robots for last mile delivery.

In the context of AGVs, the task of navigation can be divided in the three sub-tasks of

- the abstraction of the working environment,
- the planning of a global path and
- the execution of a resulting trajectory following the path.

The primary approach towards abstraction of the working environment in a mixed indoor and outdoor environment is done by extending established solutions for indoor use cases into the mixed indoor and outdoor environment. [8] describes the use of simultaneous localization and mapping (SLAM) in mixed indoor and outdoor scenarios, without addressing path planning as part of the holistic task. A hierarchical approach for the representation of the working environment using SLAM generated maps on an execution level and a connection graph on the planning level suitable for navigation purposes is described in [9]. Addressing the high demand on memory and processing power generated by a single map, a semantic approach with autonomous detection of traversing areas and triggering of corresponding SLAM configurations is shown in [10]. While the potential of SLAM for localization and map generation in static environments with a high number of references is indisputable, the applicability for holistic navigation in mixed indoor and outdoor scenarios is low. The main reasons can be found in the limited environmental information provided by maps generated using onboard sensors and the necessity for prior recording of maps to allow for autonomous navigation.

[11] addresses the problem of poor scalability using metric maps by combining a topological planning layer with multiple local SLAM maps enabling for flexible pathing while simultaneously resulting in significantly improved planning times and comparable performance to metric maps. However, this approach still depends on map generation with onboard sensors prior to autonomous navigation. Yet it shows the clear advantages of a hierarchical approach for navigation.

For pathing of AGVs in mixed indoor and outdoor environments, graph-based solutions using topological or hybrid maps show clear advantages over metric maps for large and changing environments. Combined with adequate solving algorithms, an optimal path can theoretically be found at any time with little computational demand, if all relevant factors are known to the system. [12]

Alternative approaches for unknown working environments skip global path planning and instead focus on a reactive concept for trajectory execution, by using vision sensors combined with artificial intelligence. This approach yields similar results to an uninformed path planning algorithm for changing environments. [13,14]

An approach towards a flexible navigation based on changing environmental conditions is detailed in [15] with a focus on an adaptive localization for mobile robots in indoor and outdoor environments using an Extended Kalman Filter (EKF). However, the solution is based on an already planned trajectory with inherent information to control the sensor sources accordingly and cannot be transferred to general logistic tasks.

The state of the art shows that there are multiple solutions for the abstraction of working environments as well as path planning and execution for AGVs. Using inherent information regarding the working environment in conjunction with optimized planning and execution however has not yet been investigated in the area of mixed indoor and outdoor intralogistics.

3. Hierarchical Framework for navigation of AGVs

Based on the analysis of related work it becomes apparent, that no solution yet is suitable for the flexible navigation of AGVs in mixed indoor and outdoor scenarios. The abstraction of the working environment must ensure that even large deployment environments are aggregated in a suitable way so that the corresponding storage and implementation effort before deployment is reduced. At the same time, relevant information for global path planning must be preserved. Specifically metric information as well as different environments and their influences on the operation of the vehicles have to be considered. Global path planning must be realized in a way, that all information, namely current environmental conditions, the physical setup of the AGV as well as traffic rules is taken into account. Similarly, the execution of a path has to be reactive and optimized based on the area of operation. To meet these requirements, we propose a hierarchical framework for navigation of AGVs using a node-based representation of the working environment with inherent information for global pathing and local trajectory execution, as shown in figure 2.

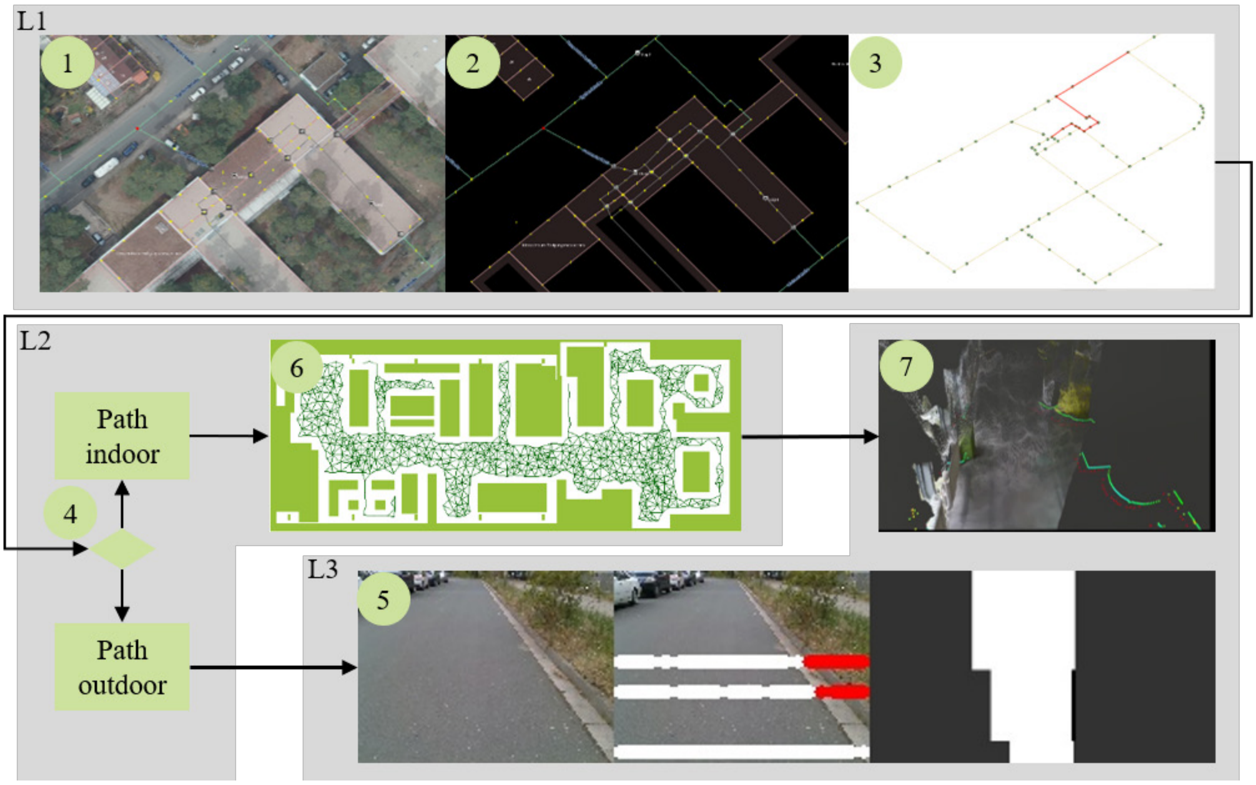

Figure 2: Hierarchical framework for navigation of AGVs in mixed indoor and outdoor operation, starting with a metric map of the whole working environment (1), a node based representation in hybrid format (2) and top level graph planning (3) followed by inherent decision making for indoor and outdoor navigation in the second layer (4) with a definition of driveable regions for outdoor areas (5) and a combination of probabilistic roadmaps (6) and local trajectory planning (7) for indoor areas.

3.1 First layer: Top level navigation using a node-based representation of the working environment

An adequate digitization of the working environment in a suitable format for flexible navigation of AGVs in mixed indoor and outdoor environments is achieved by using a node-based representation following the osm standard. Based on absolute coordinates of single points (nodes) and relations between them (ways) as well as self-defined key-value pairs for inherent information, a complete digitization of relevant information is possible. The resulting hybrid map contains a topological description of the working environment with metric information encoded in the coordinates of each node (as seen in Figure 2 Pos. 2). The map is stored in an xml-like format, which is imported into a database and evaluated predicated on defined metrics. Intrinsic information about the environment of each node (indoor, outdoor or transition) as well as restrictions in traveling speed and direction for ways are saved inside the xml file similar to a navigation approach for pedestrians presented in [16].

Utilizing the topological map on each AGV in addition to configuration files for weight manipulation based on each vehicle`s capabilities and the current environmental conditions, a directional graph with specific costs for each way is generated. This graph is then used for top level path planning using an A*-Algorithm to find the optimal top-level path between the current position of the AGV and its destination, as shown in figure 2, Pos. 3. If a reconfiguration is necessary, each node can be used as a new starting point with adjusted weights based on the changed conditions.

The list of nodes to travel for the AGV is exported as a file with comma separated values stating the number and order of nodes to travel, the coordinates of each node in GNNS format, the travel distance between each node and the environmental flag corresponding to each node. Additionally, for indoor nodes, a corresponding flag for a detailed map is given. This list is used by the second layer of navigation.

3.2 Second layer: Global path planning based on inherent information of the top-level path

The second layer of navigation is responsible for path planning in an environmentally global context, e.g. inside one production hall or connected outside areas. Based on the environmental flag of the node list inside the csv-file, the AGV is able to choose the optimal method for global path planning based on the current environmental conditions. If a set of nodes is marked being outdoor, a direct heading approach is proposed based on the circumstance, that outdoor areas often are not well structured and rapidly alternating in nature, which makes the use of complex path planning tools less reasonable. Thus, the direct heading between two nodes of the top-level graph, calculated based on the GNNS coordinates of both nodes, is sufficient and the connecting line is given as a path.

For indoor areas however, a global pathing is proposed using a probabilistic roadmap as detailed in [17]. This allows for an optimized path planning in structured indoor areas without overhead on the top level of navigation. A linkage between the nodes of the top-level navigation and the coordinates in the global navigation context is given by static transformation between the flagged map and the GNNS coordinate frame. The use of a global pathing in the second level of AGV navigation allows for an optimized routing inside buildings similar to classic indoor use cases of AGVs, while still reducing the application of said algorithms to meaningful use cases.

3.3 Third layer: Path execution in local context

The final layer of the proposed framework for navigation of AGVs in a mixed indoor and outdoor environment is path execution in the local context. As described in 3.2, for outdoor areas only a general heading towards the next node of the top-level navigation is given. Based on the configuration linked to the specific AGV and its outdoor navigation skills, corresponding autonomous capabilities are activated to achieve a reactive local navigation. For unstructured environments we propose the definition of driveable regions based on optical sensors to define the local path corresponding to the general heading, as shown in figure 3.

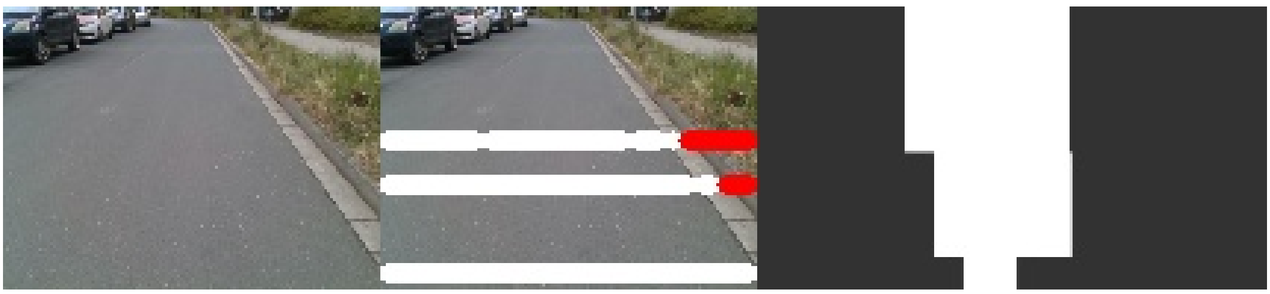

Figure 3: Definition of driveable regions based on optical sensors, showing the initial image (left) the detected driveable regions at certain ranges (middle) and the corresponding cost map for driving (right)

This definition of driveable regions ensures the operation in changing and challenging environments based on the autonomy of the system itself, similar to the capabilities of a human operator. Additionally, different configurations for image processing algorithms can be used to suit different AGVs and to consider properties like maximal height of kerbing to traverse or off-road capabilities.

For indoor areas with structured environments, standard approaches for local navigation like the Dynamic Window Approach (DWA) or Times-Elastic-Band (TEB) are suitable based on the sensors and configuration of the specific AGV. This ensures proven performance in indoor use cases with short detection ranges and a higher possibility of encounters with other road users.

4. Implementation of the proposed framework on an AGV system

To validate the proposed framework, it is implemented on an autonomous tow truck with a rugged industrial computer running Linux Ubuntu 20.04 and the Robot Operating System (ROS noetic). The node based representation of the working environment is saved as an osm-file containing the information described in 3.1. The top-level navigation is implemented utilizing a python script for loading the xml-formatted data into a PostgreSQL database with a PostGIS extension for GNNS coordinate handling and selection of the right configuration file. A second python file is executing the corresponding SQL-queries for path calculation according to the configuration file and saving of the planned path. Both python scripts are linked to an action server in ROS and can thus be executed by each AGV itself. The resulting optimal path is saved in a predefined directory and processed by an adaptive state machine addressing the evaluation and control of the second and third level of navigation. In our implementation, the software FlexBe is used for this task. Details on the functionalities and features of said adaptive state machine can be found in [18].

Global path planning and trajectory execution in the second and third layer of navigation are implemented using plugins for the standard navigation package inside ROS. According to the environment, the corresponding states inside the adaptive state machine load or unload the specific plugins for global path planning and trajectory execution inside the navigation package and monitor execution progress. Coordinate transformation between the local references of indoor maps and the GNNS coordinates is done utilizing the tf2 package and static transforms between the coordinate frames. The AGV itself is capable of autonomous navigation using different sensors detailed in [19] and is physically capable of indoor and outdoor operation.

The reference scenario for evaluation of the autonomous operation of AGVs in mixed indoor and outdoor application utilizing our proposed approach was defined at the chair of Factory Automation and Production Systems (FAPS) at the Friedrich-Alexander-University Erlangen-Nuremberg containing multiple indoor and outdoor areas connected with a manually controlled gate as shown in figure 4.

Figure 4: Reference scenario for mixed indoor and outdoor operation of an autonomous AGV using the proposed framework

5. Evaluation of the proposed framework

For evaluation purposes, transport scenarios under different environmental conditions were conducted using the implementation of the proposed approach for specified use cases. Transportation orders with mixed indoor and outdoor areas were issued and the functionality and the performance of the overall system was monitored.

As a first use case, two different configurations simulating different weather conditions for a defined transport order were issued and the behaviour of the top-level navigation was evaluated qualitatively, as seen in figure 5. The different weighting of indoor and outdoor ways for the pathing result in two different outcomes, both optimal in regards to the corresponding configuration. For weather without negative impact on safety or performance of AGVs this means outdoor traveling speeds of 8 km/h and indoor traveling speeds of 6 km/h, resulting in a travel route completely outdoors. For weather with negative impact, the outdoor speed is reduced as low as 0.001 km/h in regard to the severity of the impairment, resulting in a route mostly indoors. A speed larger than zero is needed to enable planning if no indoor route between a start and target point exists.

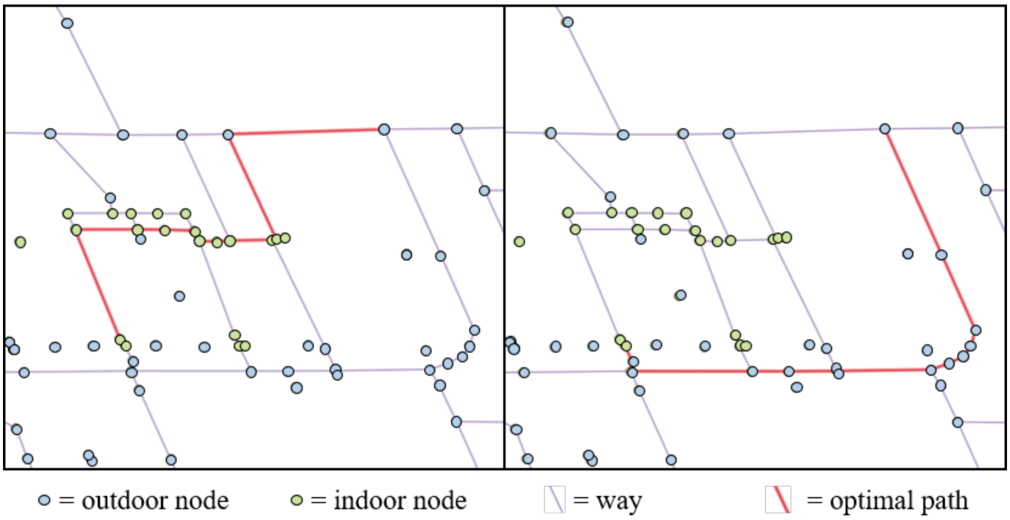

Figure 5: Results for top level navigation based on configurations simulating bad weather (left) and good weather (right)

To prove applicability to intralogistics systems, the calculation time of the approach was evaluated in addition to the functionality for the approach using normal consumer-grade hardware. Table 1 shows the needed computation time for top-level navigation in relation to the nodes inside the digitized working environment using an Intel i5-9300H CPU with 16 GB of total RAM and a SanDisk SSD. The value shows the average of 100 queries including parsing of the osm-data, path generation and saving of the corresponding data for randomly generated start and target points.

Table 1: Evaluation of calculation time depending on the number of nodes

Map file	**faps.osm**	**erlangen.osm**
Number of nodes	2113	77218
Elapsed time (s)	1.632	3.417
User CPU time (s)	0.085	0.329

Even for rather large maps, the calculation time for the top-level navigation is adequate for industrial use of AGVs in mixed indoor and outdoor environments. Performance evaluation of the different algorithms for the second and third level of navigation can be found in the corresponding publications detailed in chapter 3.2 and 3.3.

6. Summary and outlook

In this paper, we propose a hierarchical navigation for flexible use of AGVs in mixed indoor and outdoor environments. Using a node-based representation of the environment, a top-level navigation and configuration files suitable to each AGV can be used to plan optimized routes for intralogistics tasks in a holistic context. Based on corresponding flags utilizing inherent data and an adaptive state machine the use of suitable algorithms for the second level of path planning and third level of trajectory execution is enabled. The evaluation of the hierarchical approach shows the potential of the proposed framework and feasibility even for large areas of operation. However, evaluation in other mixed indoor and outdoor environments is needed for final evaluation of the limits of said framework. Additionally, the support for multiple AGV systems is possible, but not yet implemented nor tested.

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Biography

Maximilian Zwingel is a research associate at the Institute for Factory Automation and Production Systems (FAPS) at the FAU Erlangen-Nuremberg with prior research at the TH Ingolstadt since 2018. His research is focussed on autonomous mobile robots in intralogistics environments, especially their sensors and navigation.

Lukas Baier is a research associate at the Technische Hochschule Ingolstadt and head of the technology field Production control and Intralogistics. His research focusses on sensor technologies and data processing.

Andreas Blank has been a research associate at the Institute for Factory Automation and Production Systems at the Friedrich-Alexander-University Erlangen-Nuremberg and head of the technology field Industrial and Service Robotics. His research is focused on teleoperation and autonomous robots.

Prof. Dr. Jörg Franke is Head of the Institute for Factory Automation and Production Systems (FAPS) at the FAU. His research focusses on innovative manufacturing processes for mechatronic products. He is involved in leading functions in scientific organisations such as IEEE, CIRP, WGP, and 3D-MID. Before his professorship, he led different management positions in industry e.g. at McKinsey & Co., Robert Bosch GmbH, ZF Lenksysteme GmbH, and Schaeffler AG.