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Smart Maintenance Architecture for Automated Guided Vehicles

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Abstract

The increasing complexity and need for availability of automated guided vehicles (AGVs) pose challenges to companies, leading to a focus on new maintenance strategies. In this paper, a smart maintenance architecture based on a digital twin is presented to optimize the technical and economic effectiveness of AGV maintenance activities. To realize this, a literature review was conducted to identify the necessary requirements for Smart Maintenance and Digital Twins. The identified requirements were combined into modules and then integrated into an architecture. The architecture was evaluated on a real AGV on the battery as one of the critical components.

Keywords: Smart Maintenance, Automated Guided Vehicle, Digital Twin

1. Introduction

In times of digitalization and the shift towards Industry 4.0, automated guided vehicles (AGV) are a fundamental component in a smart factory to ensure an automated and flexible flow of goods in intralogistics [1,2]. The challenges posed by increasingly variable products in small batch sizes and constantly changing production conditions, which demand just-in-time provision of goods, can be solved with the help of AGVs [3]. The functionality of AGVs plays an important role in intralogistics in the course of Industry 4.0 and the development of a smart factory [4]. However, the efficiency of AGVs cannot yet be fully exploited today [5]. One reason is that today's systems are not able to react automatically to failures [5]. Downtimes of AGVs have high failure costs when causing downtimes in production systems [5]. The maintenance of AGVs faces major challenges. AGVs consist of many components, have a complex structure and therefore require a considerable amount of time to repair failure and malfunctions [5,6]. One of the reasons for this is that maintenance measures for AGVs are often reactive, as already described, and suitable maintenance personnel are not directly available [7,8]. In addition, unpredictable failures of AGVs cause high costs due to production losses [5]. The implementation and use of a digital twin have a high potential to enable greater efficiency, quality and transparency as well as a reduction of risks in intralogistics and therefore in the use of AGVs through visualizations, analyses and forecasts as well as optimization [9,10]. Isolated solutions are often used for maintenance [7]. Currently, there is no smart maintenance architecture that ensures an overall view of maintenance for AGVs. This paper presents a smart maintenance architecture that ensures an overall view of maintenance for AGVs and allows self-steering maintenance functions.

2. Related Work

Various definitions can be identified in relation to smart maintenance. According to Henke et al. *„Smart Maintenance refers to a learning-oriented, self-regulated maintenance with the aim of maximizing the technical and economic effectiveness of maintenance measures, taking into account the respective existing production system, by using digital applications"* [7].

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According to Bokrantz et al. smart maintenance consists of four dimensions [11]. These are data-driven decision-making, human capital resource, internal integration and external integration [11]. The dimensions are interlinked and support each other. Henke et al. identify six fields of action in relation to smart maintenance [7]. These include the following: Joint planning of all actors, availability-oriented maintenance, flexible acting and reacting to changes, knowledge management, requirements-based spare parts management and value contribution of maintenance [7].

To build a smart maintenance architecture, it is suitable to use the concept of the digital twin, as this enables a connection between the virtual and physical worlds and can control each other [7,12]. There are different approaches for the implementation of Architecture. Lee et al. define a five-stage architecture with a sequential workflow [13]. According to Ashtari Talkhestani et al., the first three stages smart connection, data-to-information conversion and cyber level of this architecture are necessary to realize a digital twin [14]. Redelinghuys et al. form a six-stage architecture consisting of sensors, data sources, local data repositories, IoT gateway, cloud-based information repositories, simulations, and emulations [15]. Here, humans are considered in the architecture. The human can receive information and interact with individual elements of the architecture [15]. Ashtari Talkhestani et al. additionally describe the need for synchronization and co-simulation interfaces in their architecture [14]. They also mention the necessity of using models to enable a holistic representation and behavior of the real object [14]. In their architecture, each digital twin is assigned a unique ID [14]. Bevilacqua et al. point out the need for continuous communication between the physical object and the virtual object [16]. They also see the need to implement functions such as anomaly detection and decision support in the architecture [16]. Qi et al. describe five essential components that are necessary for the construction of a digital twin [17]. These are the ability to perceive the physical world, to capture, process, and transmit data, connections within the physical world, connections between the physical and virtual worlds, and the ability to implement models and services [17].

3. Smart maintenance architecture for AGVs

Core idea is to develop a smart maintenance architecture that ensures an overall view of maintenance for AGVs and enable self-steering maintenance functions. The basic architecture represents the basic framework for the subsequent structure of the functions within the basic architecture. The basic architecture is intended to show the layers of the architecture. It could be determined that two worlds must be considered for the realization of the architecture. These are the physical world and the virtual world (Fig.1). The physical world contains the AGV and the maintenance worker. The virtual world consists of the digital twin and the communication, connecting both worlds. Communication is continuous and takes place both within the digital twin and between the physical world and the virtual world. Besides that, four main communication levels are relevant for the communication between the two worlds. These are data acquisition from the physical world, the possibility of controlling the AGV by the digital twin, the provision of information from the digital twin to the human, and the possibility of interaction between the human and the digital twin. It consists of the functional modules, which are presented in the following sections.

3.1. Module AGV

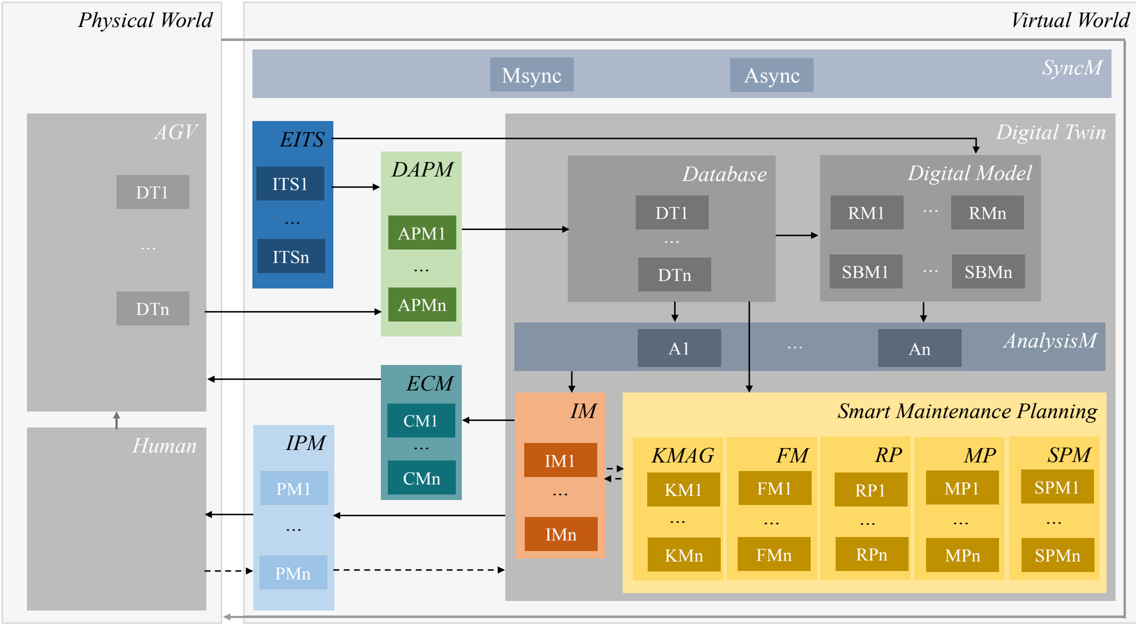
The AGV module is a partial component of the physical world and fulfills function for physical data acquisition as well as for control. The data acquired are highly depend on the structure and components of the AGV. Therefore, critical components along the components of the AGV type are identified and evaluated. Typically, these are the wheels, drive motor, steering drive, brakes, battery, etc. Suitable measurement parameters are determined that, considered individually or in combination with each other, provide information about failures and maintenance requirements. Once the measurement parameters have been identified, it must be determined whether they can be collected directly from the measurement equipment of the AGV or whether additional suitable measurement equipment must be installed in order to obtain real data from the AGV. These data can be e.g. odometry data, forces, electrical voltages and temperatures. Also, it comprises an interface such as the robot operating system (ROS) standard through which the AGV can be controlled for maintenance purposes externally, in order implement a self-steering maintenance function.

3.2. Module existing IT system

The existing IT system module (EITS) represents the function to capture data and information from existing IT systems such as file server, databases or the computerized maintenance management system. These can be, for example, process, geometry, order, material and inventory data. Furthermore, models that describe the structure and behavior of the AGV are to be transferred to the digital model module. These include electrical schematic, geometry, and simulation and emulation models. Data and information such as process, material and inventory data contained in machine-readable form are transferred to the data acquisition and processing module for processing. The EITS module is assigned to the virtual world. It has a direct link to the data acquisition and processing module and the digital model.

3.3. Module data acquisition and processing

The task of the data acquisition and processing module (DAPM) is to acquire, transform, filter, standardize, cleanse and merge data from the physical world as well as from existing IT systems. The data must be machine-readable and unambiguously assignable. In practice, it is therefore necessary to capture ID and time stamps. This allows measurement data from different measurement devices with different measurement intervals and data formats to be transformed, merged and standardized. The transformation should enable the data to be available in a uniform format. This is a basic requirement for the implementation of the module. The



Legend:

AGV: Automated Guided Vehicle
EITS: Existing IT System
DAPM: Data Acquisition and Processing Module
SyncM: Synchronizaton Module
Msync: Manual Synchronization
Async: Automatic Synchronization
IM: Information Module
ECM: External Control Module
IPM: Information Provision Module
An: Analysis
PMn: Presentation Module
APM: Acquisition and Processing Module
DTn: Data Type
RMn: Representation Model
SBMn: Simulation and Behavioural Models
AnalysisM: Analysis Module
KMAG: Knowledge Management and Action Guidelines
FM: Failure Management
RP: Resource Planning
MP: Maintenance Planning
SPM: Spare Parts Management
CMn: Control Module
ITSn: IT System

——→ Information Transmission
- - - - → Information Transmission with Interaction

Fig. 1. Functional Model of Smart Maintenance Architecture for AGV.

filtering of the data enables extraction of relevant data. The transformation, filtering and standardization initiate the step of data cleansing, in which the identification of missing measurement data or measurement errors can be specifically cleansed. In addition, it is to be checked whether the same IDs occur more than once. Another task of the module is to provide the processed data to the interfaces to the database module. The data acquisition and processing module is assigned to the virtual world. It has a direct connection to the AGV, EITS and database modules.

3.4. Module database

The database module stores the extracted and processed data. Thereby, both historical and real-time data are stored. This makes it possible to compare states of the AGV from the past with states from the present in order to create the basis for predictions about future maintenance measures in the smart maintenance planning module. This module also has the task of providing the necessary data to the digital model and analysis module interfaces. The database is connected to the data acquisition and processing module, digital model, analysis module and the smart maintenance planning module.

3.5. Module digital model

The digital model has the task of showing a holistic view of the AGV. On the one hand, it enables simulations that show the behavior of the AGV under different conditions. In addition, other models such as geometry and electrical circuit diagram models are stored. To enable a holistic description of the AGV, representative models are also required. These provide information, for example, about the current purpose of the AGV in the organization, potential further uses, expansion possibilities of the AGVs through, e.g. a trailer. The module is assigned to the digital twin in the virtual world. The module has a connection to the EITS, database, analysis module and the information provision module.

3.6. Module synchronization

The synchronization module is intended to enable synchronization of data and information between the module levels. The data and information from the module levels should be synchronized. The time cycle for the exchange is to be individually adaptable, so that the data and information exchange is adjusted and adapted as required.This module cannot be assigned to a specific entity but is generic and handles synchronization across modules. To enable synchronization, existing interfaces must be used. If no existing interfaces are available, interfaces must be created. It is necessary to define beforehand which data and information will be synchronized with which module levels. The synchronization module is a part of the virtual world in the architecture. The synchronization module is connected with all modules. The prerequisite for this module is the creation of a connection for data exchange. As long as there is no reliable connection, no synchronization can take place. It must be possible to repeat the connection establishment at regular intervals. This module offers the possibility of manual synchronization or automated synchronization.

3.7. Module smart maintenance planning

The smart maintenance planning module has the task of identifying, with the help of various module functions, whether maintenance measures of an AGV can be remedied by the vehicle itself or whether the intervention of a maintenance worker is necessary. Depending on the two different situations, suitable information for the maintenance activities is to be provided so that the information module can generate a maintenance order either for the AGV or for the maintenance personnel. The smart maintenance planning module comprises interconnected functions for maintenance planning, resource planning, knowledge management and action guidelines, failure management and spare parts management.

The maintenance planning function is used to determine whether a maintenance activity can be carried out by the vehicle itself or whether the intervention of a maintenance personnel is necessary. If a maintenance personnel is necessary, a suitable maintenance worker is identified and informed about the maintenance task. In addition, the maintenance worker receive a solution catalog, which is intended to support him in carrying out the maintenance task. To make this possible, the smart maintenance planning module interacts with the information module. The information module sends failure information that has currently occurred or will occur in the future to the maintenance planning module function. The maintenance planning module compares the failure with the failure management module function. Here, the failure is firstly classified. It is checked whether it is a failure that can be executed directly by the AGV itself via the external control module (ECM) or whether a maintenance worker is required. In the case that the AGV can repair the failure itself, the module function sends a feedback to the information module that contains information for the order generation. Possible failures where self-steering maintenance can be applied are wheels, drive motor, steering drive, brakes, battery, etc. If the failure cannot be repaired by the AGV, information is compiled via the module functions spare parts management, failure management, knowledge management and action guidelines and resource planning to enable order generation. This information includes the failure type, time of failure and failure severity from the module function failure management and solutions of the failure type with action guidelines from the module function knowledge management and action guidelines. In addition, further information is provided from the module functions resource planning and spare parts management. The information that is necessary from the module function resource planning is the availability of personnel. The spare parts management function checks whether the necessary spare parts are available. In case that the required spare parts are available, the information about the warehouse location is also transferred. If the spare parts are not available, information is transferred that shows the necessary spare parts as well as contact data of the supplier, the costs for the spare parts and the estimated delivery time. This information from the individual module functions is combined and transferred to the information module to generate an order. In addition, checklists, maintenance intervals/dates, inspection plans, components overview, manufacturer documentation, internal documentation and previous maintenance reports can be accessed interactively. These should be customizable so that checklists, maintenance reports, internal documentation and maintenance intervals as well as data from maintenance staff can be edited and modified by the information provision module. In addition, there is a direct link from the database module to the smart maintenance planning module in order to transfer the latest data, such as availability of personnel in the resource planning function or availability of spare parts in the spare parts management module function.

The resource planning module function has the task of managing information on maintenance staff. It records whether the maintenance personnel are available, what role he plays in the organization and whether he has the necessary qualifications to perform the demanded maintenance task.

The failure management sub module consists of the module functions failure classification and failure database. The failure classification function has the task of classifying failures, e.g. whether a maintenance task must be remedied by a maintenance personnel or whether the AGV can carry out the corresponding task on its own. The failure database function stores the failures that have occurred in a database. The failures are classified according to type and severity, and assigned a unique ID and timestamp. In addition, the failure database should be expandable by the maintenance personnel with additional information describing the failure and the context.

The spare parts management sub module consists of the module functions digitized spare parts information and spare parts inventories. The digitized spare parts information function provides the maintenance personnel with information on spare parts. These are divided into assemblies, individual parts or raw materials and provide the necessary information about costs, suppliers including contact details and the dimensions of the spare parts. The spare parts inventories provide information on whether and which spare parts are available, as well as information on delivery times for unavailable spare parts. It also shows at which locations the available spare parts are located. Optionally, this module can be extended so that a purchase requisition is issued automatically if required. The smart maintenance planning module is a part of the digital twin digital twin in the virtual world. It is connected to the database, the information module and the information provision module.

3.8. Module information

The information module has the task of collecting the data from the analysis module and comparing it with the failure database. Through interaction with the smart maintenance planning module, an order is generated according to the situation. This can either be sent to the ECM if the maintenance can be performed by the AGV or to the information provision module if the maintenance personnel has to perform the maintenance task. The necessary information is obtained by the smart maintenance planning module so that the order can be generated and sent. The information necessary for order generation is described in the smart maintenance planning module. It has connections to the analysis module, the smart maintenance planning and the external control module. The information module is a part of the digital twin in the virtual world.

3.9. Module analysis

The analysis module has the task of performing comprehensive analyses using the collected data from the database module and the simulated data from the digital model module. In this process, the data is first merged. This module already contains predefined analysis methods. The appropriate analysis method is selected depending on the case to be analyzed. With the help of these analyses, existing failures are to be identified and forecasts of future failures and maintenance requirements are to be made possible. The results will be transferred to the information provision module. Furthermore, the possibility of a routine performance review by suitable maintenance personnel should be given, where adjustments are made regularly in order to optimize the analyses. On this basis, the information is to be transferred to the information module. A prerequisite for the success of this module is the selection and implementation of suitable analysis methods that are regularly adjusted with regard to their performance. The analysis module has links to the database, digital model, information module and information provision module. It is a part of the digital twin in the virtual world.

3.10. Module external control

The external control module (ECM) has the task of controlling the AGV and causes an action in the AGV. These actions are rule-based and can be implemented for different scenarios. The external control module has connections to the AGV and the information module. It can be assigned to the virtual world. The external control module communicates with the AGV and provides it with the necessary information, enabling self-steering maintenance actions.

3.11. Module information provision and interaction

The information provision and interaction module has three main functions. One function is to receive maintenance orders. Another function is the provision of information for the execution of maintenance relevant activities from the maintenance planning module, which should also be viewable in offline mode, so that location-independent access is possible. The information is prepared in such a way that the maintenance personnel can act intuitively. Necessary activities as well as correlations are to be identified quickly in order to carry out the necessary maintenance measures. This is made possible with a semantic search input function. In addition, it comprises the access to the results of the simulations from the digital model, the analyses from the analysis module and documents on previous activities. The third function is the interaction of humans with the module and include documentation functions of the relevant maintenance activities, such as checklists, directly on a mobile device. Furthermore, it is required to enable access to the maintenance planning module in order to be able to transfer new failures that have occurred to the failure database. The adjustments of the modules digital model and analysis are to be made available to a certain assigned role, with which an authorization is necessary around the desired function to accomplish. Also, the module includes communication components for internet access, telephony and access to cameras. The internet access is necessary to receive current information about maintenance orders and to obtain necessary information that is not directly available via the web browser or the intranet, as well as to communicate via e-mail or messenger. The function of telephoning is to enable internal as well as external communication. With cameras, photos or videos can be made, which will be stored in the documentation. Optionally, a function could be added that assigned maintenance personnel can reject the orders. In addition, maintenance personnel should be able to transfer failures directly to the failure database. The information provision module can be assigned to the virtual world. It has connections to the human, digital model, analysis module, information module and smart maintenance planning.

4. Prototypical Implementation and Validation

The different modules forming the smart maintenance architecture for AGVs have been implemented and validated in a manufacturing lab environment. Here, the Neobotix MMO700 has been selected as AGV platform. In an experimental setup the AGV was moved under various conditions and the individual implemented modules were tested for their functionality and performance.

The AGV module was implemented by identifying critical components of the AGV. In addition, relevant parameters were identified providing information about a potential failure. In the use case the battery was identified as a critical component. Accordingly, the prototype implementation of the smart maintenance architecture was focused on the battery. The relevant parameters that were identified are state of charge (SoC), remaining useful lifetime (RUL), energy consumption (EC) and driving time under given battery level. After the identification of the parameters, it was checked whether the parameters can be acquired directly on the AGV or whether additional measuring equipment is required. Parameters such as uptime, temperature, battery charge level, odometry and voltage were recorded via the internal sensors of the AGV. A current clamp was attached to measure the current and power.

The data acquisition and processing module was implemented in an automated and rule-based manner, so that data sets that are available in different data formats are converted. In addition, different measurement intervals are normalized, cleaned and merged into a uniform format. This module was realized using Pycharm. In the digital model, a simulation was created using Matlab to simulate the behavior of the battery under different conditions. In addition, the key figures already described were calculated.

A Neo4j NoSQL graph database was used to implement the data storage. Within the graph database, various nodes and labels were created and connected. These were created for knowledge management and action guidelines, fault management, resource planning, and spare parts management. Individual links were stored in the graph database that can be accessed. This guides maintenance personnel to the documents. In addition, an interface was created that allows data from the simulation to be transferred to the graph database. The graph database serves both as a data repository and as a smart maintenance planning module, as the individual links within the nodes contain instructions that show the maintenance personnel exactly which documents or steps need to be completed and executed. In addition, further information about the storage of spare parts and tools as well as supplier information is included. Furthermore, it is possible to directly view which maintenance employees have already assisted in the rectification of specific failures. Within the database, interlinks have been implemented that allow easy completion of the necessary maintenance documents via Google Docs as file storage. The information module was implemented by a database query, which time-dependently queries individual values in the graph database and sends orders to the information provision module or external control module. The external control module has the task of externally controlling the AGV. For this purpose, a predefined driving job is transmitted to the AGV via a ROS API. In case of a required maintenance, the external control module generates an order for the driving job, which navigates the AGV to a predefined maintenance area. In this maintenance area, the AGV shuts down, for example, to avoid consequential damage to other assemblies. In this case, the external control module generates an order for the driving job, which navigates the driverless transport system to a predefined maintenance area. Overall, through the implementation, integration and test of the modules the feasibility of the smart maintenance architecture for AGVs was confirmed.

5. Conclusion and outlook

This paper presents a smart maintenance architecture for AGVs using a digital twin. The human is also part of the architecture and interact with the individual modules within the physical and virtual worlds. The architecture was implemented and the feasibility of the architecture was confirmed with in a manufacturing lab environment. Future research activities are required to determine how well the smart maintenance architecture can be implemented to different AGV types in industry and how well the smart maintenance architecture performs in the industry.

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