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Development and implementation of an autonomous control system for target-optimised use of intralogistics transport systems in the Learning Factory Werk 150 at Reutlingen University

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Abstract

Rapidly changing market conditions and global competition are leading to an increasing complexity of logistics systems and require innovative approaches with respect to the organisation and control of these systems. In scientific research, concepts of autonomously controlled logistics systems show a promising approach to meet the increasing requirements for flexible and efficient order processing. In this context, this work aims to introduce a system that is able to adjust order processing dynamically, and optimise intralogistics transportation regarding various generic intralogistics target criteria. The logistics system under consideration consists of various means of transport for autonomous decision-making and fulfilment of transport orders with defined source-sink relationships. The context of this work is set by introducing the Learning Factory Werk 150 with its existing hardware and software infrastructure and its defined target figures to measure the performance of the system. Specifically, the important target figures cost and performance are considered for the transportation system. The core idea of the system's logic is to solve the problem of order allocation to specific means of transport by linking a Genetic Algorithm with a Multi-Agent System. The implementation of the developed system is described in an application scenario at the learning factory.

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Keywords: intralogistics; target optimisation; transport systems; autonomous control systems

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1. Introduction

Due to saturated markets and a large number of substitution goods in most markets, many companies are forced to be highly flexible and offer short reaction times regarding their production. These challenges demand a high degree of flexibility and adaptability both from the production system and from the adjoining in-house material supply [1]. Conventional logistics planning and control systems were not designed to meet these requirements. These systems are usually based on a predetermined plan with a fixed allocation of the transport orders to the means of transport. The means of transport are assigned to predefined areas and routes within the production for transportation. This means that the system cannot react to unpredictable events and change the created plan in real-time [2]. Also, it is often not possible to provide all decision-relevant information to a central system in the required time and to derive control measures according to a defined target system.

To be able to optimise the internal logistics systems, the problem can be approximated with the so-called vehicle routing problem (VRP) [3]. This is based on the travelling salesman problem (TSP), in which a traveller must select the sequence for visiting several cities in order to keep travelled distances to a minimum and finally return to the point of departure [4]. In practice, the control of logistics systems regarding sequence planning represents a non-deterministic polynomial-time hardness (NP-hard) problem [5]. Consequently, optimal plans that have a realistic dimension cannot be created in a reasonable period of time. Heuristic methods, which try to reach a good achievement of the target criteria in a reasonable time, but without guaranteeing an optimal solution are mainly used in practice [6].

For solving the VRP, recent work has applied Genetic Algorithms (GA) with Embedded Neighbourhood Search, which is based on a heuristic design. In order to practically apply a GA with Embedded Neighbourhood Search for a VRP, the design of these algorithms has to be enhanced to integrate boundary conditions in practical intralogistics scenarios. A GA with Embedded Neighbourhood Search was developed for the Learning Factory Werk 150 (LFW150) to allocate the transport orders to the various available means of transport. Therefore, the realised test and validation as well as the production environment of the LFW150 is first described and then the developed algorithm is presented.

2. Test and validation scenario at the learning factory at Reutlingen University

The LFW150 at the Reutlingen University creates a realistic production environment to develop and test current issues of applied research, as well as new methods, tools, future technologies and control methods for logistics systems. Thus, the LFW150 serves as a production company, especially focusing on processes like system engineering, logistics, production and additive manufacturing [7].

At the LFW150 it is possible to assemble, store, pack, and ship multivariant city scooters. The city scooter consists of approximately 60 single components and is available in different sizes, shapes and colours. For the production, the assembly plant is equipped with lightweight robot systems, autonomous guided vehicles (AGVs), communication and information technology as well as additive manufacturing technology [8].

To validate the developed autonomous control system, a testing and validation scenario has been realised at the LFW150. The scenario covers dynamically occurring transport orders with predefined material sources and sinks for small batch size production down to a batch size of one. The considered transport systems differ in their technical properties and degree of flexibility, increasing the complexity of selecting the optimal transport systems for each transport order. In the following section, the existing hardware and software required for the implementation of the system in the LFW150 are described.

2.1. Decentralized IT system environment of the learning factory

For real-time production control, the Self Execution System (SES), which performs typical tasks of a Manufacturing Execution System (MES), is used in the LFW150. The SES, using BECOS oneiroi 2.0 framework, is able to plan production, schedule and execute orders. It offers the opportunity to simulate various production principles

and scenarios by taking existing orders and available resources into consideration. Order prioritisation, communication between all entities based on event-logic, and providing operator interfaces with relevant information takes place in the SES [8]. Centralised systems or system functionalities can be transferred into the decentralised planning and control of the SES [9]. For the implementation of the autonomous system in the LFW150, virtual agents with the corresponding attributes of the used hardware systems, described in the next section, were created in the SES.

2.2. Used hardware system of the learning factory

The transport and mobile (collaborative) robot systems used within the scenario are all based on the autonomous mobile robot platform MPO-700 of the company Neobotix. By using 2D laser scanner, the robot platform captures the layout of the production and determine the exact position of the transport vehicle based on a Simultaneous Localization and Mapping (SLAM) algorithm. Therefore, the transport and robot systems are capable to independently calculate the transport route and navigate autonomously through the production. The applied AGV, and the mobile robot platform with a collaborative Kuka Iiwa robot manipulator mounted on its top are running with a proprietary programming and platform control software with a user-friendly GUI for a simplified use (PlatformCtrl from Neobotix). In addition, a collaborative tigger train system developed with the research project “Kollaborativer Routenzug 4.0 (KollRo 4.0)” using the open-source Robot Operating System (ROS) framework is used to test and validate the developed autonomous control system.

The Telocate Assist localisation system is used for the indoor-localisation in the LFW150, using radio or (ultra)sound signals and is connected with the SES. Localisation takes place via a tag by sending an acoustic signal in the range of 18–21 kHz [10]. Depending on the reception times of the transmitted signal at the individual receivers, the position of the smartphone or tag can be calculated. The calculation of the reference positions takes place as a self-calibrating process during operation [9].

2.3. Logistics target criteria of the learning factory

To be able to determine the target achievement of the research objectives, suitable target figures are required for measuring the logistical performance of the system. Target figures are the basis to assess and improve the performance of logistics systems [11]. Based on the originally described target system for production logistics by Wiendahl, the target system for the control of intralogistics means of transport in the production environment of the LFW150 has been extended [12].

The target system for the LFW150 distinguishes between two target systems. One target system considers the transport order for the city scooter and the corresponding A parts, parts with a high-value share and a low-quantity share, referred to as ‘target system for the means of transport’. The other target system considers the supply of the production line with C parts, parts with a low-value share and a high-quantity share, named ‘target system for the KollRo’.

The reason for the distinction between the two target systems is that two different transport systems, which work independently, are considered for these tasks. The transport of the city scooter and the A parts is carried out by the means of transport AGV, KukaIiwa and human. For the transport of the C parts to the production line, only the KollRo is responsible.

3. Development of a Genetic Algorithm with Embedded Neighbourhood Search

For optimal use of the means of transport according to the defined logistics target figures, the solution space is searched with the help of an algorithm. The aim is to find the best possible solution in a reasonable time considering several objective functions according to the target figures in Section 2.3. The objective functions distinguish between the ‘target system for the means of transport’ and the ‘target system for the KollRo’.

The logic of the algorithm is shown in Fig. 1, consisting in its core of a population comprising a certain number of chromosomes. Each chromosome represents a sequence of transport orders defined by a specific source to the desired sink. Thereby, each customer order for a new city scooter comprises a number of transport orders. During the solution search new solutions are generated from the chromosomes by using different operators such as mutation (creating new solutions by changing the sequence of transport orders within a chromosome), crossover (combining two solutions of individual chromosomes) and mutation with local knowledge (agents change the sequence of transport orders within a chromosome based on their knowledge). In addition, the new generated solutions are assessed concerning technical violations in the allocation of transport orders such as duplication or deletion of transport orders. If these solutions show an improvement, the fitness evaluation and the selection of the solution for the new population of the following generation is executed. The acceptance mechanism selects which individual chromosomes are taken into the new generation. After the optimisation run is determined, the best solution is applied for the intralogistics control [13].

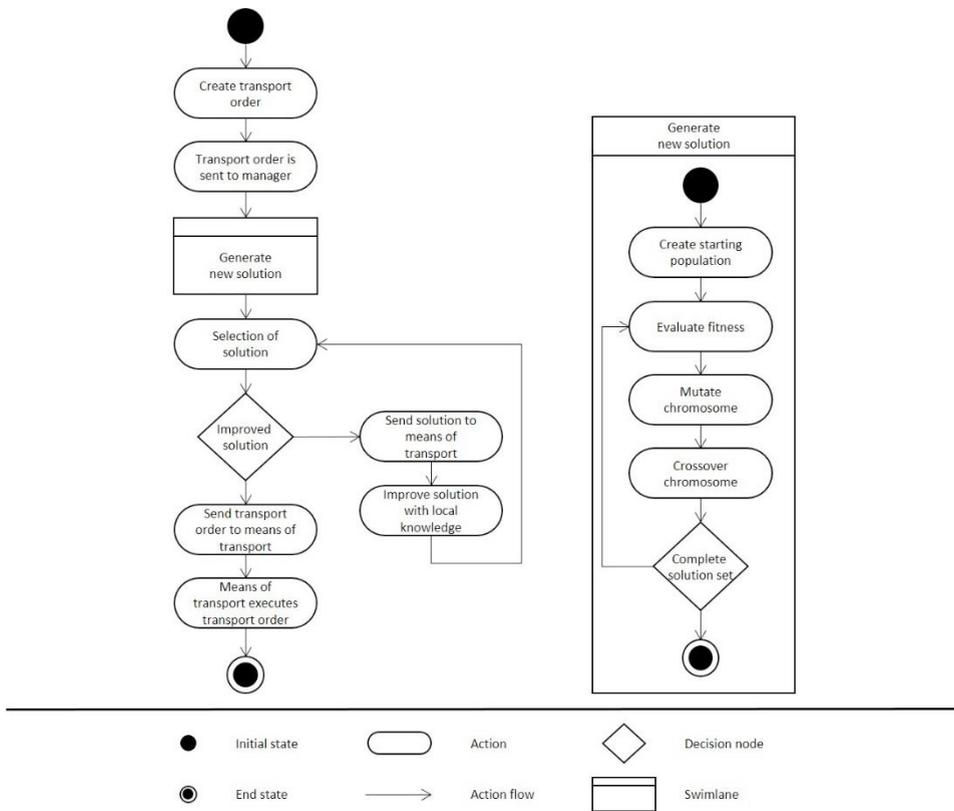


Fig. 1. Activity diagram of the algorithm for sequence optimisation [13].

4. Implementation of the system

In order to test the successful integration of the developed system into the LFW150, a list of requirements was defined. Table 1 describes the six requirements (Req.) for the complete integration of the autonomous system into the LFW150. Following the table, the implementation of the individual requirements is described. A complete implementation of the autonomous system in the LFW150 was not possible due to the relocation to a new building. At the time of implementation and validation, not all hardware systems at the LFW150 were operational.

Table 1. Requirements for a complete implementation of the system in the Learning Factory Werk 150.

Req.	Description of the requirements	Degree of fulfilment
1	Customer orders can be created and imported into the SES	●
2	City scooters, A parts, C parts and means of transport are locatable in the LFW150	◐
3	City scooters, A parts, C parts are able to send their current condition to the SES	◑
4	The logistic target criteria of the system are visualised and measurable	●
5	The means of transport can calculate the transport route and navigate autonomously through production	●
6	The means of transport can receive and assess transport orders and submit a transport proposal themselves	◐

○ Unfulfilled ◐ Underperformed ◑ Partially fulfilled ● Sufficiently fulfilled ● Fulfilled

For the implementation of the system in the LFW150, the Requirements 1, 4 and 5 were completely fulfilled. Regarding Requirement 2, the localisation of all logistical objects through the Telocate Assist localisation system is not yet possible. Due to the relocation of the LFW150 to a new building only two of the Telocate tags were installed and functional for testing at the time of implementation. The system still relies on the processing time at the workstations based on a methods-time measurement (MTM). The fulfilment of *Requirement 3* is complete as soon as the city scooter, A part and C part are able to send information about ID, type of order, source, sink and delivery time to the SES. The identification of the orders of a city scooter, A parts and the C parts should take place via an integrated RFID tag with the corresponding information. For the completion of *Requirement 6*, the human should be able to update its state like ‘ready’ or ‘in repair’ and send the information via a web-controlled application to the SES.

5. Results

To demonstrate the abilities of the algorithm, verification of the developed system as well as a validation in the LFW150 was performed. The results of the verification showed that by using the Genetic Algorithm with Embedded Neighbourhood search, the target figures of the logistics performance of the means of transport AGV, Kukaliwa and human are of great importance for high numbers of orders in the system. Allocating a high number of customer orders to the means of transport is more difficult, since the number of possibilities increases exponentially. The target figures of the logistics costs are becoming increasingly important in case of small numbers of transport orders in the system since less possibilities of combining transport orders exist. Also, the KollRo in the autonomous system is able to ensure a higher degree of target achievement than the KollRo in a central system.

For the validation of the autonomous system in the LFW150, an event validity test is carried out. For the test series, an order for a new scooter was loaded into the system every five minutes. The input value ensures that on the one hand, the system was still observable during the validation process; on the other hand, the number of customer orders loaded into the system was sufficiently high to impose a certain required flexibility on the system. The processing times of the city scooter at the respective station were based on the fixed times of the MTM.

During execution the number of transport orders, the information of source and sink, the selection of the means of transport for the respective transport order, x- and y-position of the means of transport, utilisation time of the means of transport and time of empty runs of the means of transport were monitored. The verification and validation tests proved on the one hand that the assumptions of the system were valid and on the other hand that there were significant improvements over central planning and control systems. It also outlined the importance of the flexibility and adaptability of the intralogistics systems with regard to the logistics target criteria performance and costs.

6. Conclusion and next steps

The Genetic Algorithm with Embedded Neighbourhood search has proven its potentials in many fields including the VRP. By extending the algorithm in this paper, it was possible to prove the ability for the use of practical intralogistics scenarios. In future, for a complete implementation of the system in the LFW150, the condition monitoring of the city scooter, A parts and C parts will be integrated. By using RFID tags, the status of the city scooter will be tracked. For the automated monitoring of the stocks of the C parts in the production, the smart bin system as described in Vogt, Hummel, Schuhmacher, von Leipzig, & Louw [14] will be integrated into the system. Furthermore, the total fleet of transport systems, for example the AGVs, will be integrated into the system. Also, the tablet's user interface will also be expanded and improved for a more intuitive operation and display of all necessary information.

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