Development of a Hybrid Control Approach for Automotive Logistics Based on Close to Real-Time Information Management

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Abstract—Nowadays, logistics processes are mostly controlled by applying a central control approach. This approach often neglects changing conditions within the supply chain after planning. Therefore, regarding an increasingly complex and dynamic environment, the central control approach often turns out to be inflexible and not manageable satisfyingly. Here, a decentralized approach, so-called autonomous control, provides an alternative as it enables logistics objects to react autonomously and flexibly on changing conditions. Herein, it is indispensible to exchange information with other participants of a supply chain to identify changes which occurred after planning. Both, the centralized and the autonomous control approach, feature advantages and disadvantages regarding performance and information transparency. A hybrid control approach promises the combination of these advantages.

In this paper we introduce the characteristics of automotive networks and related control approaches. By referring to a practical example we present a possible specification of relevant information in automotive logistics and underline the importance of a well-designed information management. Following this, we present a development process to derive an efficient method for hybrid control.

Keywords—Automotive Logistics, Autonomous Control, Close to Real-Time Information Management, Hybrid Control.

I. INTRODUCTION

DURING the last decades the general conditions of the automotive industry have changed. Individual customer demands, new drive technologies and innovations have lead to a constantly growing number of product variants [1], [2]. In this situation, automotive manufacturers focused on their key competences and reduced their vertical integration of manufacturing [1], [3]. As a result, complex production and logistics networks have grown within the automotive industry. Due to the increasing globalization these networks often span around the world. In order to plan and control these networks efficiently information is required. This information must be collected and exchanged close to real-time among the participants of the supply chain, to react flexibly to unexpected events. Here, late, incorrect or incomplete information leads to inventory fluctuations and prolonged lead-times thus affecting the overall performance of the supply chain [4]. In order to collect and exchange information close to real-time and preferably automatically, first of all the technical infrastructure has to be defined and implemented. The exemplary development and implementation of the required infrastructure is attended to within the research project 'RAN - RFID based Automotive Network' funded by the German Federal Ministry for Economics and Technology (BMWi). The general objective of this project is to increase information transparency within networks of production and logistics of the automotive industry applying RFID (radio frequency identification) [5]-[7]. Accordingly, a method to generate and integrate logistics and product-specific information in internal and interplant tools for job control will be developed. This method bases upon the standardized exchange of process relevant information which allows the control of the value chain of automotive logistics close to real-time.

Against this background, central control of logistics processes was observed to be inflexible and not manageable [8], due to an environment that becomes more and more complex. Particularly complete re-schedulings, e.g. necessary due to disturbances or delayed material deliveries, are difficult in many cases. This often NP-hard problem can only be solved in an acceptable effort by heuristics, as the dynamic environment may cause the calculated plan to lose its validity before it can be realized [9]. In order to cope with highly dynamic conditions an autonomous decentralized control approach was suggested within the Collaborative Research Centre 637 'Autonomous Cooperating Logistic Processes: A Paradigm Shift and its Limitations' at the University of Bremen [8]. Thereby, intelligence and the ability to reach decisions are transferred from central control to the logistics objects themselves. This decentralization of decision-making leads to the ability of a whole system to react autonomously and flexibly to new requirements of a fast changing environment. Hereby, the robustness and the positive emergence of the complete system can be increased [8], [10]. A current research task in this context is the comparison of autonomous control and central control in terms of logistics objectives in varying situations of dynamics and complexity. To investigate this question a functional interrelation which

compares the achievement of logistics objectives for different levels of autonomous control and complexity has been suggested [11]. This inter-relation is a first approach to examine the limitations of autonomous control. In addition, Scholz-Reiter et al. present a method to determine an adequate level of autonomous control and explain different possibilities of decentralization [12]. These developments indicate the advantages provided by a combined approach of autonomous and conventional control. Here, the levels and degrees of both approaches are controlled dynamically to fit the situation. This partial decentralization of control within logistics systems is described as hybrid control in literature [13], [14]. However, so far the general idea of hybrid control has not been studied in detail, especially regarding alternative specifications, characteristics and its impact on the achievement of logistics objectives.

In this paper we present the development process for an efficient method of hybrid control applicable for the example of automotive logistics. In the next section we describe the complexity of automotive logistics and specify information necessary for the efficient control of these networks. Subsequently, we introduce related control approaches and their general advantages and disadvantages in this field of application. Finally, we introduce the development concept of a method for hybrid control which allows combining the advantages of the established control approaches.

II. COMPLEXITY IN AUTOMOTIVE INDUSTRY

In this section, logistics networks are described generally as well as the processes of automotive logistics using the example of a practical use case that is analyzed within the project RAN [7]. Based on this use case, relevant information in a supply chain and related control approaches used in automotive logistics are described. The scope of the investigation comprises the process of vehicle movement between storage areas and stations of technical treatment at an automobile terminal, which are points of transshipment usually operated by a logistics service provider (LSP).

A. Complex logistics networks of automotive industry

Generally speaking logistics can be described by 7Rs: the task of logistics is to guarantee the availability of the right product, at the right time, at the right place, in the right amount, for the right customer, with the right quality and at the right costs [15]. These criteria are particular important within the automotive industry, e.g. considering concepts of Just-in-Time (JIT) and Just-in-Sequence (JIS) deliveries. However, logistics networks are very complex in these cases so that delivering in JIT or JIS makes huge demands on everybody along the supply chain. This complexity is caused by the fact that an original equipment manufacturer (OEM) has a huge number of suppliers which in turn might come with a huge number of suppliers themselves, Fig. 1. The resulting structure is described by referring to different tier-levels indicating the distance in terms of levels between an OEM and his supplier.
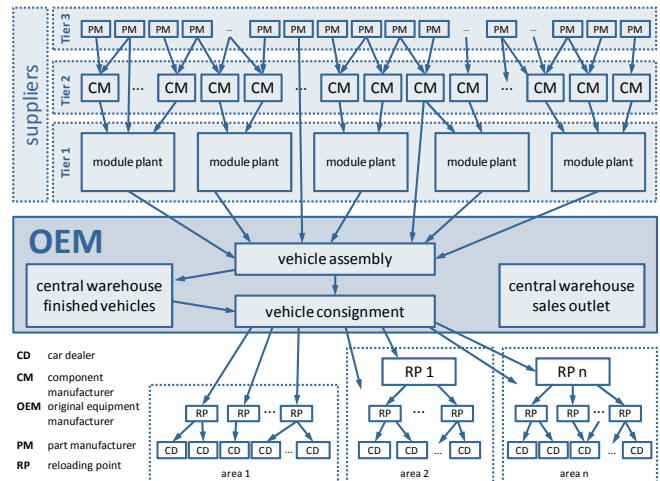

Fig. 1 network of automotive logistics (following [17])

The complexity of the related supply chains is pushed by multilateral material exchanges within the network structure, e.g. the transfer of parts of the final product by the OEM to the supplier [16]. Furthermore, automotive supply chains often include imports and exports before the finished vehicles are distributed within the widespread network of car dealers. In addition, between the vehicles' production at the OEM and their sale at a car dealer, there are mostly a considerable number of turnover points.

With globalization, the conditions of the automobile industry have changed. Today, there is a worldwide demand for specific product variations with individual customer demands. At the same time, vehicles as well as components are produced all over the world. As a consequence, the automotive industry has developed the described complex networks, in which a multitude of products is being produced simultaneously. Because of the high complexity of these global networks even small deviations from production planning can cause increased lead times and rising costs – especially if these deviations are not communicated in time among the participants of a supply chain. Thence, it is of particular importance to provide the control of automotive logistics with actual and close to real-time information, which must be exchanged within the whole supply chain.

In addition to internal processes and data, the intersecting process steps within the automotive supply chain are relevant for the design of efficient control approaches. Therefore, the global supply chain is traditionally controlled by a centralized control system.

B. Practical example of a supply chain

The examined process chain begins with starting the engine for the first time at the automobile manufacturer, Fig. 2. At the end of the assembly line at the OEM every vehicle is identified by an employee using the vehicle identification number (VIN). The VIN bijectively defines every vehicle. For the following process steps a smart label based on the VIN is placed in the rear window of the vehicle. For every further movement this smart label is used for identification. The

vehicles are transported by train from the automobile factory to the harbor. After the transshipment in the harbor from train to car vessel the vehicles are transported to the automobile terminal of the LSP in Germany.
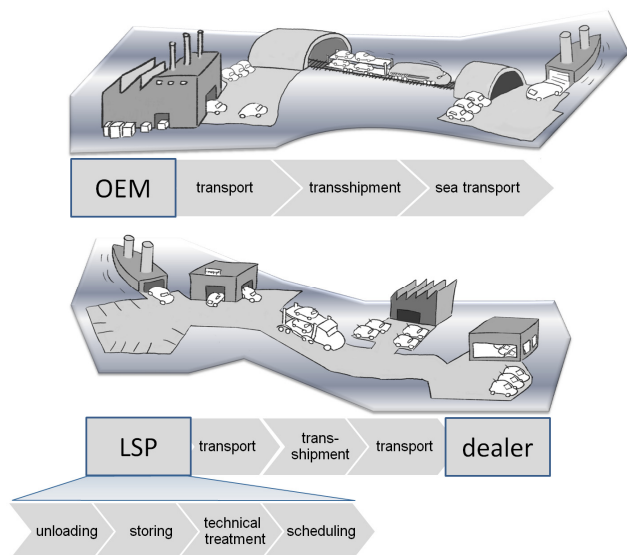

Fig. 2 exemplary supply chain of automotive logistics (following [7])

Automobile terminals provide various services for vehicles including transshipment, storage and technical treatment. After the vessel's landing the vehicles are unloaded. Terminal employees drive the vehicles to a storage area. Once the order of a car dealer comes in, requesting a vehicle with certain features, the chosen vehicle is passed through several stations of technical treatment. After that, the vehicle is brought to the disposition area for transportation to the requesting dealer. Here, the vehicles are transported by truck passing a point of transshipment to the car dealers.

The described processes at the automobile terminal are influenced by unsteady arrivals of car vessels on the one hand and unsteady orders of car dealers that define the further steps of technical treatment on the other hand. After unloading, the vehicles are stored on different storage areas. Since there is no definition of further process steps at this point of time, the vehicles are not clustered on these areas. After an order of a car dealer arrives, the required vehicles are taken out of the storage area.

In order to improve and align all mentioned processes information about arrivals of car vessels and demands of car dealers is necessary at defined points of time. These points of time and the required information from the participants within the process chain are specified in the following sections.

III. INFORMATION MANAGEMENT IN AUTOMOTIVE LOGISTICS

A. *Basics of information management*

In order to successfully cope with deviations from scheduling information must be exchanged with the participants of the supply chain [18]. Here, real-time or close to real-time information is a perquisite for an efficient overall control of the logistics processes. Cooperating businesses are more successful than individual or isolated businesses [19] because synergy effects caused by the cooperation mostly take a positive effect. Information that is provided across cooperating businesses in a transparent way offers better planning opportunities for all parties of the supply chain. This results in shorter lead times, lower costs, better profits and improved overall decisions [20]. Here, late, incomplete or incorrect information can cause considerable problems in the supply chain [4], e.g. the so called bullwhip effect [21]. However, even the exchange of too much information impedes the processes' efficiency, e.g. meaning that no participant of the supply chain has the relevant information at hand at the right time or relevant pieces of information need to be distinguished from non-relevant information first [20]. Moreover, the differentiation between relevant and non-relevant pieces of information implies increased efforts and is error-prone. Therefore, the decision which data is exchanged along the supply chain and at what time is of utmost importance. Within the next section, we specify the relevant information using the example of automotive logistics.

B. *Information management in automotive logistics*

In order to allow the participants of the supply chain to actualize and optimize their job control systems the relevant status information must be defined. This status information describes a status change. Examples of status information are "receipt of vehicles", "dispatch" and "handling finished" as well as additional status information such as "vehicle damaged" or "vehicle refuelled". As a consequence, the vehicles should be captured electronically when passing through the dispatch of a participant of the supply chain. Similarly, when passing a defined area that allows for inferences concerning the estimated handover to the next participant information should be captured and passed on to the concerned participant. This is particularly important to register the vehicle within the inventory of that station. This information does not necessarily need to be handed on in the supply chain. This is only necessary if the information affects the order control of other participants.

The information about status changes along the supply chain is detected. Here, the vehicles are identified thus generating and actualizing the system's state. Within the described supply chain, there exist numerous status changes, Tab. 1. Thereby, we differentiate between intra-company relevant and inter-company relevant information.

The job control system of the OEM requires information about the time when vehicles leave the assembly line and information about the start and the end of rework (if necessary).The time when a vehicle is forwarded is relevant for the OEM as well as for all following participants throughout the supply chain. First of all the transport service provider requires this information to start the transport process. In addition, the LSP has to consider this information within his job control system estimating the time of arrival.

Comparable to the transport and the sea transport process (see above), information is required on intra-company as well as on inter-company levels.

Tab. 1 relevant vehicles status changes within automotive supply chains (light-grey: intra-company relevant status changes; dark-grey: inter-company relevant status changes)

Participants of the supply chain	status changes			
original equipment manufacturer	assembly finished	rework start	outgoing	
		rework end		
transport	loading	unloading	transshipment	
sea transport	loading		unloading	
logistics service provider	incoming	storage	technical treatment start	outgoing
		removal from storage	technical treatment end	
car dealer	incoming			

Within the processes of the LSP status data includes information like "incoming", "storage", "removal from storage", "technical treatment start", "technical treatment end" and "outgoing", whereupon only the last information is relevant for an inter-company exchange. The other information conduces to an internal comparison of nominal and actual states. This information is non-relevant as long as no disturbances occur. However, disturbances which affect the job control system of other participants are inter-company relevant. In these cases the disturbances have to be communicated to all participants within the supply chain. Based on this communication, the participants can consider the disturbances in their own job control systems.

Based on exchanging the relevant information described above, processes of automotive logistics can be controlled efficiently and proactively. The following section presents the established control approaches in networks of automotive logistics.

IV. ESTABLISHED CONTROL APPROACHES FOR AUTOMOTIVE LOGISTICS AND THEIR ADVANTAGES AND DISADVANTAGES

A. Conventional central control

Nowadays, logistics processes are mostly controlled applying a centralized control system, e.g. a manufacturing execution system (MES). In this paper centralized control and conventional control are used synonymously. Conventional control means that all logistics objects and processes are controlled by a single and centrally located control system. These conditions also apply for the control of jobs and processes at an automobile terminal as described in section 2. The following description of the conventional control approach focuses on the presented use case, especially on the processes of the LSP.

For the described situation at an automobile terminal either arrivals of car vessels or orders of car dealers initiate the processes meaning that both events cause updates of the job control system. After the arrival of a car vessel the vehicles have to be unloaded and stored in the available storage areas. Here, the central control system has to decide in which storage area the vehicles have to be placed by using predefined rules which contain an order of priority of all storage areas [22]. Whereas the arrival of a car vessel triggers the storing of cars, the orders of car dealers initiate the removing of vehicles from stock. Furthermore, the order defines the necessary technical treatments and the related stations, e.g. for washing or charging the batteries. In this case the conventional control system decides about the sequence, in which the vehicles are processed. Summing up, it can be stated that applying a central control approach is crucial for all processes of the LSP, Fig. 3.
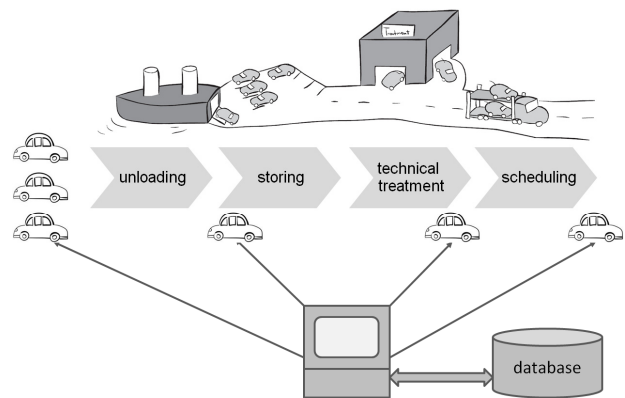

Fig. 3 conventional control of LSP's processes

The centralized decision-making at the automobile terminal has the advantage that the processes' control orients itself at global control objectives and dates within the automotive supply chain. Thus, the vehicles are primarily controlled regarding their adherences to delivery dates. Additional objectives are short lead-times and low inventories. Besides that, central control of the LSP processes features positive effects regarding the transparency of decision-making. For example, employees are informed about incidents within the centrally controlled processes. This is advantageous, as employees can identify changed terms and conditions (e.g., delayed delivery of materials) and take corrective actions. However, in an environment that becomes increasingly complex, a central control system also reveals serious disadvantages. For example one finds here often NP-hard problems addressing the complete re-schedule of the job controlling.

B. Autonomous control

Autonomous control was suggested within the Collaborative Research Centre 637 to cope with increasing complexity and dynamic environments, in which the central control of logistics processes turns out to be inflexible [8].

Within the related research, the following definition was worked out: "Autonomous Control describes processes of decentralized decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. The objective of Autonomous Control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity." [23]

Considering this definition decentralized decision-making of the described processes of the LSP means that vehicles are no longer controlled by a central control system but every vehicle controls itself through the required processes via sending requests to storage areas and stations of technical treatment, Fig. 4.
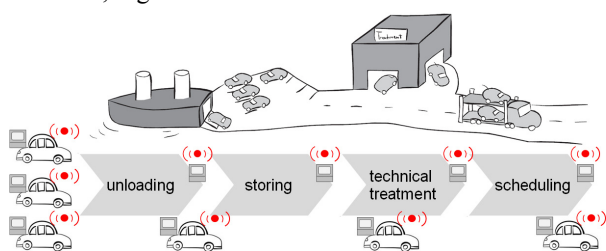

Fig. 4 autonomous control of LSP processes

For this purpose vehicles are featured with the ability to collect and to process information about the occupancy of the storage areas on the one hand and with data concerning the job status within technical treatment on the other hand. In order to enable the information exchange the vehicles are equipped with smart labels. These labels can be identified with a wearable computing system, which is worn by the employees. The reading operation starts when an employee sits in the vehicle. With the bijective identification (i.e., VIN), the vehicle is enabled to decide decentralized and autonomously by the wearable computing system which provides the calculating capacity that is necessary to make decisions. The wearable computing system communicates with other technical systems via WLAN (Wireless Local Area Network) or GPRS (General Packet Radio Service) to process information. One example is the exchange of data between the wearable computing system and the technical treatment station to receive information about the occupancy. Based on autonomous control methods, the wearable computing system has the ability to make decentralized decisions for the vehicle, e.g. to which technical treatment station the vehicle has to be driven next. [24]

Autonomous control methods suited for the processes of the LSP have already been developed within the Collaborative Research Centre 637 [25]-[27] as well as concepts of the infrastructure [28], [29] and concepts for simulation [30], [31]. The different methods of autonomous control have been analyzed regarding their achievement of logistics objectives by simulation studies. Using the example of the storage process, both, the vehicles and the storage areas, feature their own databases and act in-line with their own logistics objectives. Generally, each vehicle demands short transfer times in the terminal area whereas offering each storage area the occupancy of one storage location. Vice versa, each storage area requires occupancy offering a total transfer time to the requesting vehicles. This transfer time consists of the following subtracted times: transfer time from the current vehicle location to the storage area, parking time in the storage area (which depends on their utilization) and the future transfer time to the first technical treatment station. This total transfer time is transmitted to the requesting vehicle which compares the total transfer times given by the alternative storage areas. Considering its objectives the vehicle chooses the best-rated total transfer time. Within a simulation study it has been shown that a total saving of 112 work days within one year arises when controlling the processes and vehicles autonomously [22], [24].

Some advantages of the described processes are listed in [32]. Generally, autonomous control leads to an efficient process control while reducing the efforts for planning to a minimum. In addition, changing from centralized to decentralized decision-making pursues the objective to increase the robustness of complex nondeterministic systems [23]. But there are also some disadvantages and limitations of autonomous control. First of all, Windt et al. assumed that very high degrees of autonomous control as well as very low degrees may affect the achievement of logistics objectives negatively [11]. Moreover, global objectives may be neglected when concentrating on local and autonomous decision-making. Here, logistics objects reach their decisions regarding short transfer times and short processing times without considering externally given delivery dates. Furthermore, the approach of autonomous control limits the employees' possibilities to monitor all processes and to take corrective actions.

V. CONCEPT OF A HYBRID CONTROL APPROACH FOR AUTOMOTIVE LOGISTICS

A hybrid control approach promises the combination of the advantages of the conventional central control approach as well as the advantages of the autonomous control approach described in section IV. Furthermore, applying a hybrid control approach (based on an exchange of relevant information close to real-time) for the often complex processes of automotive logistics facilitates to react early and flexibly on changed terms and conditions. Within this section a concept of a hybrid control approach for automotive logistics is presented.

Generally, there are different possibilities to interpret hybrid control. For example, hybrid control can be interpreted as the central control of strategic processes on the one hand and the autonomous control of operational processes on the other hand. However, within this research the hybrid control approach is interpreted as the dynamic coexistence of centrally and autonomously controlled processes, meaning the ability to changeover between central and autonomous control, Fig. 5.
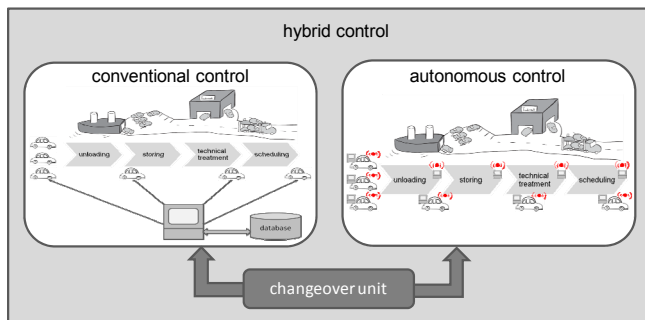
Fig. 5 hybrid control of LSP processes

The possibility of switching from conventional to autonomous control appears advantageous, when the complexity and consequently the dynamic increases. This is the case when unexpected events and process deviations, e.g. delayed arrivals of car vessels, prolonged storing processes and delayed process starts within technical treatment, endanger the globally given delivery dates within the supply chain. Here, a complete re-scheduling, necessary in these situations, is complex and often NP-hard. In contrast, a changeover from autonomously controlled processes to conventionally controlled processes appears advantageous when complexity decreases. This is the case when by reason of unpredictable events new centralized due dates have to be met within the supply chain. At the same time, this allows more transparency for the employees about the system's status allowing them to take action and to bring in expertise. In addition, changing from autonomously to conventionally controlled processes can also take advantageous effects as too high levels of autonomy can result in a reduced achievement of logistics objectives [11]. The described relationship between the achievement of logistics objectives, level of complexity and the level of autonomous control is illustrated in Fig. 6. Here, an interval is depicted in which the hybrid control approach may regulate the level of autonomous control thus guaranteeing a high level of logistics objectives achievement.
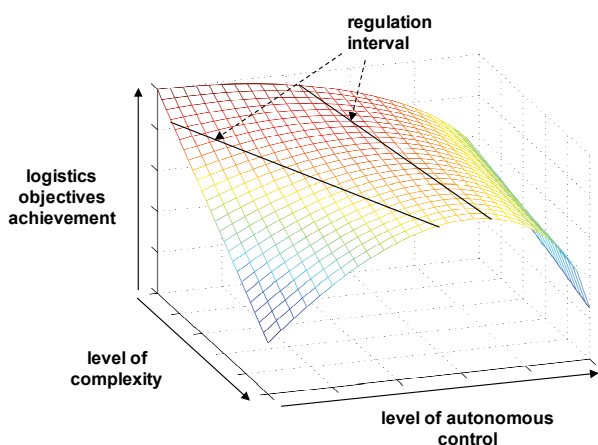

Fig. 6 dependence of logistics objectives achievement on level of complexity and level of autonomous control indicating the preferred regulation interval (following [11])

The generation of close to real-time information necessary for the hybrid control approach is mainly realized via RFID-equipment and prototypically implemented within the research project RAN (see above). However, not all relevant information can be gathered by RFID, e.g. downtimes of technical treatment stations and storage areas, or the damage of ordered vehicles caused by weather.

Within the presented research the changing over between both control approaches is going to be investigated in detail. Thereby, the impact of hybrid control on the achievement of logistics objectives in comparison to purely conventionally and autonomously controlled processes will be of particular interest. For this purpose the research will focus on the design of an efficient method to be applied within the changeover control unit.

VI. DEVELOPMENT PROCESS OF THE HYBRID CONTROL APPROACH FOR AUTOMOTIVE LOGISTICS

In order to improve the logistics performance of processes related to the LSP methods of hybrid control are developed and compared against conventional and autonomous control by means of simulation. The development process bases on the comparison of the logistics performance of these simulation runs with the results derived by a hybrid control. In the following the general idea of the development process is described.

The development process starts with a process analysis of the described scenario within automotive logistics. Here, general requirements for the development of the hybrid control method are derived. Initially, the relevant objectives and their weights are determined. Previous research solely considered the total transfer times as a measurement to quantify the performance of the applied control method [24]. This course of action neglects the consideration of times which are needed by the terminal employees to return from the storage area to the car vessel. Therefore, our approach considers transfer times as well as return times.

Previous research compared autonomous control with conventional control by referring to its real-world data [24]. Thereby, the autonomous control was estimated as an efficient approach. Similarly, the developed hybrid control method will be compared to conventional as well as autonomous control. While the results of conventional control are represented by real-world data, results of autonomous control and hybrid control will be generated applying simulations. Thus, hybrid control will be practice-based although we expect it to be more efficient in dynamic situations because of its autonomous components.

After the described determination of requirements those logistics objectives (e.g. lead-time, inventory, adherence to delivery dates, etc.) will be defined which are subject to the monitoring and comparison process later on. These measurements conduce to supervise the processes and thus to identify changed terms and conditions, which are decisive to changeover from one to the other control approach as described above. This monitoring has to be carried out close

to real-time in order to identify changed terms and conditions immediately. However, some parameters have to be defined in advance. At first, the monitoring has to be specified regarding its recording mode (periodical recording, discrete-event recording, continuous recording, etc.). Subsequently, surveillance methods have to be defined, like the application of quality control cards [33]. In this context, we will define and analyze various limits of action control which trigger the switching over between conventional and the autonomous control.

Based on the described parameters, the development of alternative changeover rules from the one to the other control approach have to be developed in detail. Thereby, the control can be changed over for every vehicle or just for the vehicles which start processing on the automobile terminal after changing over. Here, some approaches of production control are already described in literature [34]-[37].

After requirements and alternative control rules have been defined we implement the hybrid control methods in a discrete-event simulation model to test and to evaluate the control approach. In this context, we will also define requirements for the simulation model including the specification of relevant processes. Following the modeling of these processes we implement, evaluate and improve alternative hybrid control rules successively. Here, the changeover rules will differ in their parameter settings. Regarding the simulation results, we will re-parameterize the changeover rules, if necessary. Afterwards, this new parameterized methods will be investigated simulation-based concerning its logistics performance. Applying this procedure we expect to develop an efficient hybrid control method.

Once the developed method for hybrid control proves its advantages for the described scenario it will be transferred and tested within more comprehensive scenarios. Here, different parameter configurations for the switching between conventional and autonomous control will be analyzed to confirm validity extending the described scenario

VII. CONCLUSION

Due to increasing complexity and dynamics within production and logistics networks, the application of a conventional centralized control approach often turns out to be not manageable. Within the Collaborative Research Centre 637 an autonomous control approach was suggested to cope with these conditions. However, both the conventional and the autonomous control approach, feature advantages and disadvantages. Here, a hybrid control which allows switching between both, the conventional and the autonomous control, promises combining the advantages of both approaches.

The introduced approach of hybrid control for automotive logistics bases on information exchange close to real-time to react flexibly and immediately on changing conditions. However, exchanging too much as well as too little information causes additional efforts. Therefore, referring to a practical example we introduced exemplary processes and

specified information that is relevant for the overall supply chain. In addition, the paper at hand presented the development process of a concept of a hybrid control approach. This approach will be detailed and investigated in its impact on the achievement of logistics objectives compared to conventional and autonomous control in further research activities.

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