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Multiagent Coordination Enabling Autonomous Logistics

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Abstract This dissertation develops coordination mechanisms for the implementation of autonomous control in logistics with multiagent technology. Therewith, it tackles the challenges of supply network management caused by the complexity, the dynamics, and the distribution of logistics processes. The paradigm of autonomous logistics reduces the computational complexity and copes with the dynamics locally by delegating process control to the participating objects (such as shipping containers). The dissertation specifies and implements the cooperative problem-solving process for autonomous logistics. The presented solution has been used in a realistic simulation of real-world container logistics processes. The validation shows that autonomous control is feasible and that it outperforms the previous centralised dispatching approach by significantly increasing the resource utilisation efficiency.

Keywords Agents · Cooperation · Autonomous Logistics · Supply Chain Management

1 Logistics Requirements

Automating process control in logistics is a challenging task because supply networks grow increasingly complex, dynamic, and distributed. Logistics optimisation (like for the well-known Vehicle Routing Problem) is dealt with in the field of operational research (OR). Conventional centralised approaches to logistics control, however, turn out to be feasible only for well-defined subproblems [?]. In particular, they frequently focus on individual primary logistics functions such as transport in the case of the Vehicle Routing Problem, thereby neglecting other aspects such as storage.

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By contrast, real-world supply networks are highly interconnected. The economic globalisation causes supply networks to span over multiple continents and to involve a high number of participants. The so-called goods structure effect denotes an increasing number of shipments to an increasing number of individual receivers. If one took all logistics objects and their manifold parameters into account, the combinatorial complexity for conventional process control would be no longer manageable for adaptive planning. In addition, the dynamics of logistics processes can render optimal plans outdated already in the moment their generation is finished. Furthermore, the spatial distribution of logistics processes often prevents information from being available centrally on time. Central control is thus frequently not feasible for adaptive planning and control of a complete logistics system

The paradigm of autonomous logistics [?] aims at overcoming these limitations by delegating decision-making to the participating logistics objects. Based on objectives imposed by their owners, these autonomous logistics entities (represented by software agents) can themselves plan and schedule their way through logistics networks. Each agent incorporates only its own parameters as well as those of cooperating agents. Therefore, the computational complexity can be reduced significantly and dynamics can be dealt with locally. This vision requires not only granting the autonomy, but also delegating the ability to make decisions to the logistics objects. New technologies in identification, localisation, sensor, communication, and data processing enable logistics objects, such as shipping containers, to make decisions on their own. This work implements the decentralised decision-making as well as the coordination of the individual autonomous logistics entities, therewith enabling the application of autonomous control in logistics to real-world process control. Employing agents on embedded systems is not a prerequisite for the developed approach. The advantage of problem decomposition is also retained if the agents are deployed on a server or server cluster.

2 Multiagent-Based Operationalisation

Multiagent systems are an appropriate paradigm to implement autonomous control in logistics. The characteristics of intelligent agents [?], i. e., autonomy, reactivity, pro-activeness, and social ability, directly reflect the requirements for autonomous logistics entities. Although the problem decomposition reduces the computational effort, another challenge arises: Despite their autonomy individual logistics entities can usually not satisfy their objectives individually. In Distributed Artificial Intelligence this problem is addressed by the cooperative problem-solving process [?]. It formally specifies the four steps required for agent cooperation, starting from the identification of a potential for cooperation, over team and plan formation, to joint team action. Particular interaction schemes, however, are underspecified as this concept is rather general and thus abstract. Therefore, this dissertation contributes specific interaction schemes for autonomous logistics [?].

As first step, the dissertation determines the potential for cooperation by examining the participants in autonomous logistics processes. On the one hand, the participants cover general cargo units (such as shipping containers or cardboard boxes) as consumers of logistics services. On the other hand, also providers of logistics services, such as transport, handling, storage, and picking, pertain to the participants. The motivation for cooperation between these agents is threefold:

1. Cooperation helps complement insufficient individual capabilities (e. g., a shipping container needs help from a means of transport to be transported).
2. Cooperation increases the resource utilisation efficiency (e. g., a shipping container should not be transported alone on a barge or train).
3. Joint action of objects with similar goals reduces the interaction effort, thereby preventing that the reduced computational complexity is outweighed.

This means that there is not only a potential for cooperation, but cooperation is an important prerequisite for autonomous control in logistics.

This results in the next question to be dealt with, namely how logistics objects can actually form teams for joint action. Previous approaches mainly focus on forming teams of agents with complementing capabilities. Usually, these approaches incorporate a relatively small number of agents. They are finished as soon as an agent for every task is found. While this is also important in autonomous logistics, the main focus is rather on forming large teams of agents with similar logistics demands. For instance, one wants to group all shipping containers that demand transport from the same location to the same destination. As elaborated above, this helps utilise resources more efficiently and decrease the interaction effort. To achieve this goal, teams must allow participants to join later because potential participants are not necessarily known in advance. Moreover, assuming that all logistics objects pertain to the same company, it must be ensured that no competing teams with same properties are created concurrently.

Based on these requirements, three different agent interaction protocols are proposed. They can also be employed for applications beyond logistics because the descriptors (e. g., type, location, time) by which team formation is conducted are generic. The protocols are based on a directory, a broker, and multicast messaging (Figure 1), respectively. Their most distinguishing properties are the degree of decentralisation as well as the interaction effort to be spent for team formation. The interaction effort increases with the degree of decentralisation. Even in the worst case, it does not exceed $O(n^2)$ for n agents, usually it is much lower. Based on this finding, the potential as well as limitations for autonomous logistics are derived analytically. Regarding the team formation mechanisms, this analysis allows for choosing the appropriate interaction scheme for a specific application in autonomous logistics.

Based on the team formation mechanisms, the joint action of agents in autonomous logistics is accomplished in the following steps:

1. The allocation of logistics services by individual autonomous logistics entities is operationalised.
2. This approach is extended to the joint allocation of logistics resources by teams of service consumers.
3. Finally, also the intra-agent coordination of multiple logistics functions is solved.

It is worth mentioning that the teams for allocating the different primary logistics functions (such as transport or storage) are usually not identical. The last step addresses this issue and allows agents to coordinate their membership in different teams and thus the utilisation of multiple logistics resources. Therewith, this thesis provides a complete implementation of the general cooperative problem-solving process for autonomous logistics.

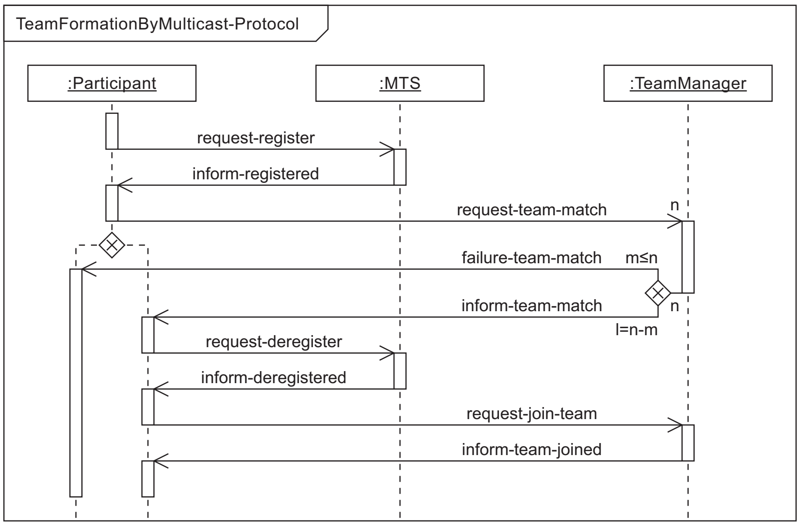

Fig. 1 For team formation by multicast, new participants optimistically register as team managers (by subscribing for respective multicast messages with the message transport system). Then, they check with the already registered managers whether none of them already covers their descriptor. If there is a conflict, they deregister themselves and join the existing team.

3 Application

Real supply chains are highly individual and differ significantly between companies. This means that there is no overarching prototype. Therefore, a real-world supply chain with particularly challenging logistics requirements has been chosen for evaluation. A major European retailer of consumer products provided insights into its processes and, similarly important, real-world process and dispatch data. The company procures a large part of its products in East Asia. For transport, these goods are packed into shipping containers and forwarded to the container terminals in Bremerhaven and Hamburg. The specific process examined in this dissertation is onward carriage, i. e., transporting the containers from the domestic container terminal to the warehouses of the company. For each arriving container, about 30 parameters have to be considered for dispatch. These parameters do not only cover the intended sales date of the cargo. Moreover, a warehouse that is capable of receiving the cargo has to be identified. For instance, oversized articles cannot be received in a high-bay warehouse and valuable goods must be secured. Furthermore, available capacity for transport, handling, and storage must be coordinated.

The investigated process exhibits a high degree of complexity and dynamics. The project partner has more than 1,200 own stores and over 56,000 points of sale in total. In order to replenish these sales outlets with new articles, every week more than 200 containers from East Asia arrive in the ports of Hamburg and Bremerhaven. Transport from East Asia to Europe takes between two and six weeks which means that, in total, even more containers have to be monitored continuously (by means of the 30 parameters mentioned above). This complexity is even aggravated by the dynamics of the process. The company offers its customers a weekly changing range of products. From this follows, that each article actually has to be in the stores on time. Moreover, the products differ regarding their value, weight, and physical dimensions which significantly impacts the logistics demands. Finally, delays must be dealt with that are caused, for instance, by unreliable suppliers or traffic and weather conditions.

Hitherto, human dispatchers control this process manually, supported only by information systems. Only two experts are capable of this highly specialised task. This low redundancy affects the process reliability because much of the process knowledge is in the head of only two humans. Problems might occur when the experts are ill, take their vacation, or change to another position. The reason why the company still chose this approach is that previously there was no automated method for process control available that fits the sophisticated requirements of this process (which holds for many complex processes in supply chain management). Although software solutions exist for individual primary logistics functions (such as warehouse or transport management systems), there is no comparable solution for the integrated control of these functions. Apart from the highly individual processes on the level of supply chain management, the main explanation is the complexity resulting from this integration: the high degree of complexity of discrete linear programming (which is NP-complete) simply prevents realtime process control.

The paradigm of autonomous logistics is particularly suited for such problems because it reduces the complexity by decentralising process control. Decentralisation alone, however, is not sufficient. Coordination is required, for instance, to jointly use means of mass transport such as barges and trains. Furthermore, similar goods should be stored in the same warehouse (as long as sufficient capacity is available) in order to reduce transport costs in the subsequent distribution process. For this purpose, the coordination mechanisms developed in this dissertation can be employed because they support team formation based on the required spatial, temporal, and type-based criteria.

4 Evaluation

The transition from previously manually controlled processes to autonomous control has been implemented on the JADE agent platform and has been validated with the PlaSMA simulation middleware. Multiagent-based simulation has a high modelling accuracy because of its natural mapping between the real-world objects and their simulation counterparts. As opposed to equation-based modelling, the behaviour of agents in simulation directly corresponds to their behaviour in real-world operation. For comparing the new approach to the status quo of process control, the project partner provided real process and dispatch data. The original data set is confidential business data and can, consequently, not be made publicly available. To deal with this limitation, the original data has been analysed regarding its relevant parameters. The identified parameters (published in the dissertation) support reproducing and benchmarking by means of synthetical data that resembles the original data. For the evaluation, the behaviour of over 11,500 shipping containers that arrive over the time-span of one year is examined.

The first hypothesis to be investigated is that the decentralised approach can actually satisfy the challenging logistics requirements. Several strategies for the allocation of storage and transport resources were evaluated (differing, for instance, in the time when decisions are made). It turned out that cooperating agents are actually capable of allocating the required logistics resources efficiently and reliably. Depending on the strategy chosen, the total time for simulating dispatch for one year ranges between 15 and 50 minutes. Even in the worst case, dispatch for each container takes less than a second which makes the approach feasible for realtime control. The approach can therefore be employed to relieve human dispatchers from standard cases. Therewith, the dispatchers can concentrate only on exceptional cases that cannot be covered by the multiagent system and, thus, provide better dispatching results in these cases than before when they had to handle them under time pressure.

The second hypothesis is that the multiagent system does not only keep up with the previous approach, but actually outperforms it. This hypothesis can be motivated by the fact that the high number of logistics objects and their parameters often overburdens human dispatchers. In such cases, the dispatchers consider only the most relevant parameters and follow their experiences otherwise. Indeed, the validation reveals that the agent-based approach exceeds the efficiency of the manual one. The pickup of containers can be deferred (without compromising process integrity), thereby utilising free storage times at the container terminals. This helps save costs by reducing storage capacity required in the warehouses of the project partner. The simulation of the onward carriage process shows a potential for savings of 2.6 million pallet-days per year.

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