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PROJEKT

An Agent-based Approach to Autonomous Logistic Processes

Collaborative Research Centre 637: Autonomous Cooperating Logistic Processes

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Abstract This paper presents the research activities of the Collaborative Research Centre (CRC) 637 "*Autonomous Cooperating Logistic Processes—A Paradigm Shift and its Limitations*" at the University of Bremen. After a motivation of autonomous logistics as an answer to current trends in increasingly dynamic markets, we sketch the structure and aims of the interdisciplinary CRC. We present several interpretations of the central motive of autonomous control, pursued by sub-projects over the course of the first project period, and focus on an agent-based approach to autonomous logistics.

1 Introduction

The increasing pace of structural change in today's globalized markets bears significant implications for logistic processes with regard to adequate planning and control strategies. The formation of alliances, e.g. virtual enterprises and global logistic supply networks, leads to increasingly complex processes in many logistic branches such as procurement and distribution. The transition from traditional vendor-driven markets to so-called buyers' markets with far-reaching customer focus as an important competitive factor coincides with an increase in overall volume of cargo shipments. Also, we observe market trends towards smaller cargo units, mass customization and higher delivery frequencies. The dynamics and structural complexity of logistics supply networks thereby often inhibit the provision of crucial information for central decision-making instances or the timely computation of global production or transport schedules.

Consequently, there is a growing demand for adaptive logistic processes with autonomous control capabilities, tailored specifically for decentralized coordination of intelligent logistic objects. The autonomy of such objects, e.g. loading equipment or transportation systems, can be implemented by means of emerging information and communication technologies. Radio Frequency Identification and electronic product codes extend unique identification of goods from the product level down to individual items. Wireless communication and the proliferation of logistic infrastructure with sensors and embedded systems enable auto-identification, end-to-end tracking and tracing, and interaction of intelligent logistic entities in forthcoming logistic systems.

2 Joint Research on Autonomous Systems

At the University of Bremen, the CRC 637[1] lays scientific groundwork with a broad research of the concept of autonomy and develops a novel control paradigm for real-world logistic processes. The goal is to harness the full potential of (a) the increasing pool of real-time monitoring and process flow data, (b) the synchronization of material and information flow, and (c) the combination of auto-ID and information services in the so-called "*Internet of Things*" [3]. The

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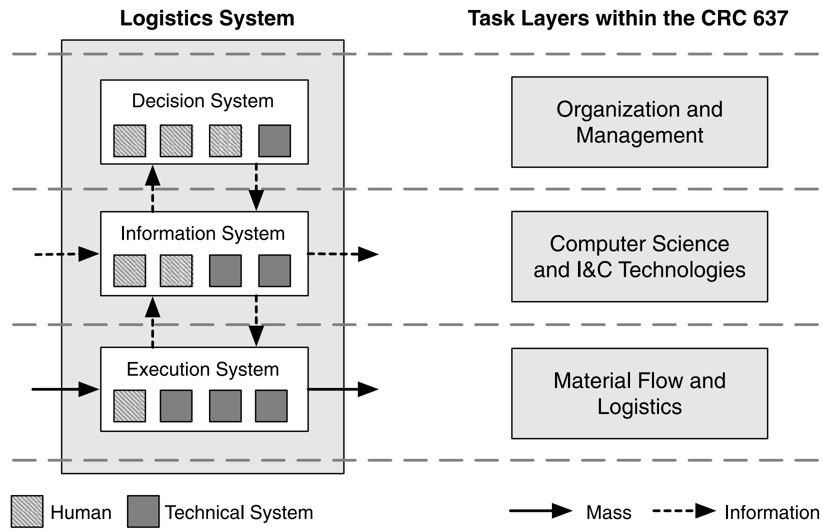

Fig. 1 Schema of the three task levels within the CRC 637

CRC seeks to decentralize control strategies which, due to their flexibility and adaptivity, persist in complex economic environments characterized through continuous change, taking into account global corporate goals.

Subject of research of the CRC 637 is the autonomous flow of physical goods and commodities as well as the management of self-monitoring logistic processes (cf. Fig. 1). The holistic view on autonomy encompasses self-organization concepts from management theory and self-monitoring concepts from both natural- and engineering sciences. Due to the large number of logistic sub-processes along modern value-added chains, the CRC focuses specifically on production and transport logistics. Research in the CRC 637 is currently organized in sixteen sub-projects with more than sixty researchers in total. These have expertise in production technologies, economics, computer science, electrical engineering, and mathematics. The sub-projects are associated with one of the following project domains: foundations in modeling of autonomous logistic processes, methods and tools, and applications.

In the first period (2004–2007), the main focus of the CRC was on the development of a sound theoretical basis and common understanding of the autonomy paradigm [10]. Currently, in the second project period (2008–2011) focus is shifted towards the application of attained findings in concrete autonomous control methodologies and tools. With the establishment of four transfer projects, the CRC has also initiated intensive efforts to transfer its research results into the economy.

3 Views on Autonomous Control

A fundament of research in the CRC 637 has been a joint definition of autonomous control, phrased by Hülsmann and Windt in [10, p. 59] as "*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.*"

Due to an interdisciplinary approach, several perspectives on the interpretation of autonomous control in the context of logistics have been developed. Kreowski et al. propose a strict formalization of logistic actors as *autonomous units* for the modeling of logistic systems [12]. Graph transformation with these units can be related to the use of multiagent systems (MAS). Kopfer *et al.* propose autonomously controlled adaption of formal decision models in the context of operations research [17]. Scholz-Reiter *et al.* consider approaches for modeling and analyzing shop floor scenarios in production logistics including discrete-event simulation, system dynamics and analytical models in form of differential equations [16]. Becker *et al.* investigate the propagation of self-organization concepts, which have been developed and used originally for routing in large-scale communication networks, into the logistics domain [1].

3.1 Autonomous Agents in Logistics

In the following we focus on the research of the knowledge management sub-project of the CRC 637. In this project, we have identified rational agents and MAS as a vantage point for conceptual modeling and simulation of cooperating logistic decision makers. For this research, we concentrate in particular on situation-aware agents which extend and substantiate the classical rational agent definition [21]. For this category of agents, their respective belief about the world is no longer taken for granted. It is rather actively controlled by information acquisition as an additional meta-level reasoning process [5, 13]. Modeled *decision makers* in our interpretation include both human controllers in logistic processes and inanimate entities, such as shipping containers, which have been augmented with autonomous control capabilities.

The benefit of multiagent technology for the modeling of autonomous logistics is brought about by dynamic interaction, facilitated by the MAS' ability to follow predefined organizational structures or bring forth emergent structures from dynamic interaction. In order to warrant efficient operation in large real-world MAS, we assume that it is to some degree necessary to administer interaction and communication among agents. This can be realized based on the concept of roles and structures, known from organization theory [20]. Here, behavior roles constitute an abstraction of functions from particular agent instances.

4 Knowledge Management in MAS

Our conception of knowledge management tasks is strongly influenced by the agent perspective. We consider (a) adequate knowledge representations for autonomous agents in logistics, (b) goal-directed, autonomous knowledge acquisition and integration, (c) knowledge exchange and dissemination among agents, and (d) collaborative learning of contextual models.

With regard to the representation of non-fluent domain knowledge in the field of logistics, several domain-specific ontologies have been compiled which formalize and explicate transport networks, transport and production logistics, and physical goods. These ontologies have been tied together initially in a ground ontology built specifically for this purpose. Current efforts in knowledge representation comprise an alignment of the existing logistic ground ontology with the DOLCE[2] foundational ontology [15]. Such an alignment renders possible the integration of the specialized domain ontologies in DOLCE; a useful basis to facilitate semantic mediation. Based on DOLCE's *Descriptions and Situations* module, the formalization of an agent activity in context is cast in a separate descriptive ontology employing pertinent logical- and content patterns [4].

In the first period of the CRC 637, the projection of knowledge management functions on behavior roles and consequently the interplay of these roles in logistic contexts have received special emphasis [13]. Logistic interaction protocols were also developed for team formation of intelligent shipping containers, seeking to reduce, amongst others, transport costs [19]. In the current CRC period, the focus of attention is broadened to knowledge-based autonomous systems that require up-to-date knowledge to decide on their next course of action.

The design of such systems is particularly challenging if they cannot rely on their own sensory capabilities alone but also need to acquire additional knowledge about distant locations. Such an acquisition is realized through information exchange with other agents [5]. Other challenges include the requirement to infer future states of the environment and to assess the current situation context. The relevance of a specific information for situation assessment is determined by the current plan and other potential plans under consideration. Usually, this is implicitly specified by the decision system. Problems arise if the decision-relevant information is not available to the agent. With missing situational information, the system would not be able to assess a situation correctly. For instance, detection of a harmful risk might be inhibited because the agent has a lack of information which it is not aware of [14]. Hence, autonomous systems have to perform situation assessment that enables them to detect missing information. Due to bounded resources, this detection process must be governed and prioritized by information relevance. If the sensory capabilities of the agent alone cannot provide required information, other agents or information sources need to be inquired. Only autonomous systems possessing such meta-level reasoning capabilities are able to have true situation awareness. Our approach to implement the meta-level reasoning for information acquisition [5] draws from the fields of information value theory and decision networks.

5 Evaluating MAS via Simulation

Multiagent-based simulation (MABS) applies the concepts of multiagent systems to simulation. According to Herrler and Klügl [9, p. 575], "*it is a perfect means to represent and examine emergent effects in distributed systems. Multi-agent simulation models may be used to gain insights into system interdependencies, to make predictions and also for testing software systems.*" MABS can be categorized as distributed simulation with discrete time model. It combines simulation scalability and run-time acceleration with encapsulation of decision-making in agents. Recently, MABS has seen increasing popularity for simulating complex models of economic markets and social networks, which feature large numbers of concurrently operating, dynamically interacting sub-processes.

General-purpose agent development frameworks are for the most part designed without specific consideration of simulation. In particular, they do not provide means for simulation time management which guarantees controlled discrete progression of simulation time for all (inter)acting agents. To that end, we propose a synchronization strategy which constitutes a compromise between the prevention of a parallelization bottleneck (and thus limitations to simulation speedup) and synchronization management costs [18]. We also identify and formalize time model adequacy, causality,

[2] *Descriptive Ontology for Linguistic and Cognitive Engineering*.

and reproducibility as quality criteria for message passing among agents. These need to be ensured by a simulation middle-ware implementing synchronization. These research results have been implemented in the multiagent-based simulation environment PlaSMA[3] Based on the FIPA[4] [18]. compliant agent platform JADE [2], PlaSMA constitutes the common basis for distributed simulation experiments, used by various sub-projects in the CRC 637. It has been deployed successfully for hybrid experiments which closely interconnect multiagent-based simulation of a large-scale transport scenario with an intelligent shipping container in the real world, equipped with temperature sensors and an embedded agent platform [11]. Further simulation experiments realized with PlaSMA comprise the examination of the influence of knowledge exchange among agents in dynamic collaboration networks and the utility of up-to-date environmental information. We used information available in preprocessed or even plain textual form for local route planning performed by transport agents of a freight forwarding company [6]. The latter simulation scenario was elaborated further such that the competitive performance of transport agents with access to different extents of environmental information could be evaluated in simulation [8].

With regard to the medium-term goal to propagate multiagent-based implementation of logistic decision and control systems from the lab into real-world production systems, MABS is considered a suitable means to test multiagent applications for compliance with specifications at hand. Although multiagent-based applications are initially deployed in a simulation test bed in early stages of their product life-cycle, agent developers should be put in a position where they can focus exclusively on the production use case. We therefore propose to augment multiagent-based simulation environments such that simulation-specific portions of the agent code bases are no longer required [7]. This renders possible a *uniform agent design* suitable for both simulation and operation. The characteristics of the agents' target environment, either real or simulated, is kept transparent from the point of view of the agents. Working towards the uniform agent design ideal, the PlaSMA system is currently extended to handle implicit simulation time synchronization [18].

6 Summary

In this survey, we have identified challenges for the field of logistics that are induced by coalescence of international markets and the increasing pace of structural change. The CRC 637 approaches these challenges via a transition from the traditional centralized logistic management and control paradigm towards local autonomy of logistic actors. We focus on an agent-based approach to implement the aspired paradigm shift. First promising steps have been taken on the way towards knowledge-based rational agents that can assess their respective activity context and take advantage of such capabilities in their decision processes. Further research will also incorporate decision making models for knowledge-based rational agents as well as collective learning of contextual models.

[3]"*Platform* for *Simulations with Multiple Agents*" Web site: http://plasma.informatik.uni-bremen.de.

[4]*Foundation for Intelligent Physical Agents*.

References

1. Becker M, Singh G, Wenning B-L, Görg C (2007) On mobile agents for autonomous logistics. Int J Serv Oper Inform 2(2):114–130
2. Bellifemine F, Poggi A, Rimassa G (2000) Developing multi-agent systems with a FIPA-compliant agent framework. Sofw Pract Exp 31(2):103–128
3. Fleisch E, Mattern F (eds) (2005) Das Internet der Dinge—Ubiquitous Computing und RFID in der Praxis. Springer, Berlin
4. Gangemi A (2005) Ontology design patterns for semantic web content. In: Musen M et al (eds) Proc. of the fourth international semantic web conference. Springer, Berlin
5. Gehrke JD (2009) Evaluating situation awareness of autonomous systems. In: Madhavan R, Tunstel E, Messina E (eds) Performance evaluation and benchmarking of intelligent systems. Springer, Berlin, pp 93–111
6. Gehrke JD, Langer H, Herzog O (2008) Distributed control for robust autonomous logistic processes. In: Robuste und sichere Logistiksysteme. Wissenschaftssymposium Logistik, vol 4. Deutscher Verkehrs-Verlag, Hamburg, pp 25–37
7. Gehrke JD, Schuldt A (2009) Incorporating knowledge about interaction for uniform agent design for simulation and operation. In: 8th international conference on autonomous agents and multiagent systems, pp 1175–1176
8. Gehrke JD, Wojtusiak J (2008) Traffic prediction for agent route planning. In: 8th international conference on computational science 2008, vol 3. Springer, Berlin, pp 692–701
9. Herrler R, Klügl F (2006) Simulation. In: Kirn S, Herzog O, Lockemann P, Spaniol O (eds) Multiagent engineering: theory and applications in enterprises. Springer, Berlin, pp 575–596
10. Hülsmann M, Windt K (eds) (2007) Understanding autonomous cooperation and control in logistics. The impact on management, information and communication and material flow. Springer, Berlin
11. Jedermann R, Behrens C, Laur R, Lang W (2007) Intelligent containers and sensor networks approaches to apply autonomous cooperation on systems with limited resources. In: Hülsmann M, Windt K (eds) Understanding autonomous cooperation and control in logistics. The impact on management, information and communication and material flow. Springer, Berlin, pp 365–392
12. Kreowski H-J, Kuske S (2008) Communities of autonomous units for pickup and delivery vehicle routing. In: Proc. of the 3rd international workshop on applications of graph transformation with industrial relevance. Springer, Berlin, pp 281–296
13. Langer H, Gehrke JD, Hammer J, Lorenz M, Timm IJ, Herzog O (2006) A framework for distributed knowledge management in autonomous logistic processes. Int J Knowl-Based Intell Eng Syst 10(4):277–290

14. Lorenz M, Gehrke JD, Hammer J, Langer H, Timm IJ (2005) Situation-aware risk management in autonomous agents. In: Proc. of the 14th ACM international conference on information and knowledge management. ACM, New York, pp 363–364
15. Masolo C, Borgo S, Gangemi A, Guarino N, Oltramari A (2003) D18: Ontology library (final). Project deliverable, WonderWeb: Ontology infrastructure for the semantic web
16. Scholz-Reiter B, Wirth F, Freitag M, Dashkovskiy S, Jagalski T, de Beer C, Rüffer B (2007) Mathematical models of autonomous logistic processes. In: Hülsmann M, Windt K (eds) Understanding autonomous cooperation and control in logistics. The impact on management, information and communication and material flow. Springer, Berlin, pp 121–138
17. Schönberger J, Kopfer H (2007) On decision model adaptation in online optimization of a transport system. In: Management logistischer Netzwerke: Entscheidungsunterstützung, Informationssysteme und OR-Tools. Physica-Verlag, Heidelberg, pp 361–381
18. Schuldt A, Gehrke JD, Werner S (2008) Designing a simulation middleware for FIPA multiagent systems. In: 2008 IEEE/WIC/ACM international conference on web intelligence and intelligent agent technology. IEEE Computer Society Press, Los Alamitos, pp 109–113
19. Schuldt A (2010) Multiagent coordination enabling autonomous logistics. Doctoral dissertation, University of Bremen
20. Timm IJ, Scholz T, Herzog O, Krempels K-H, Spaniol O (2006) From agents to multiagent systems. In: Kirn S, Herzog O, Lockemann P, Spaniol O (eds) Multiagent engineering: theory and applications in enterprises. Springer, Berlin, pp 35–51
21. Wooldridge M (2000) Reasoning about rational agents. The MIT Press, Cambridge

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