Usability of Multi-agent Based Control Systems in Industrial Automation

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Abstract. A future adaptive and reconfigurable manufacturing system has to address, beside the requirements for agile and fast reaction to sudden and unpredictable changes in production demands, also the problem of user acceptance and understanding of such highly intelligent reconfigurable systems. Thus, the usability is a major criterion for the design of future manufacturing systems. The design and development of both the architecture for simplifying of development of such systems and the advanced diagnostic, monitoring, and human-interaction system will provide an easy maintenance and increased acceptance of such systems.

Keywords: Usability, Multi-Agent Architecture, Automation, Diagnosis, User Acceptance.

1 Introduction

The mass production area was predominated by big investments for customized equipment, in order to produce faster and cheaper large quantities of identical or similar products. Even small changes in the product design or any failure in such a production system caused the production to stop and required a work- and time-intensive reprogramming of the system. The changing environment of today's market raises the need for new production planning and production control models and requires new approaches for production lines and intelligent machines to provide stability, sustainability, and economy under such production conditions. Being agile is important for reacting fast to sudden and unpredictable requirement changes with minimum risk. Adaptive, reconfigurable and modularly structured manufacturing systems address these requirements allowing machines and plants to flexibly adapt themselves to changing demands and interact with each other to fulfill the overall production goals.

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While physical components of such systems are available, the implementation of reconfigurable systems in the manufacturing industry is hindered by the lack of knowledge-based methods and intelligent tools for their optimal deployment and control of their operation. Currently available methods and tools for the deployment and operation of such manufacturing systems are mostly based on traditional techniques applied in flexible manufacturing systems and are quite straightforward, addressing specific problems, lacking intelligence and learning capabilities. Moreover, their application takes place off-line, requiring significant down times as well as human interference. In order to reach the full potential of such systems, the adaptation of the system's performance to an optimal manufacturing solution for the appointed task needs to take place autonomously, in real-time and with as less human involvement as possible. Thus, the development of an autonomous intelligent governing system for adaptive modular reconfigurable manufacturing systems is of outmost importance.

But seen from today's standpoint of stakeholders in automation, the engineering of such manufacturing systems is too complex and their maintenance and service is presumed to be not manageable from outside anymore. Therefore, the usability should be a main criterion for the design of such highly reconfigurable intelligent manufacturing systems. In the future, it will not only be necessary to have adaptive reconfigurable manufacturing systems with the fast set up and implementation but also a production system that will be accepted by a user.

Such autonomous manufacturing systems with a modicum of human involvement have to be able, besides the performing of scheduled operation, to recognize possible problems and prevent them or, if not possible, to react on in an appropriate way and treat the failures. The on-line built-in diagnostic system is therefore crucial for improving the performance of such a system, but the static and pre-programmed diagnostics is pointless in that case [1]. It is impossible to preview all the critical situations which might occur in the life cycle of the system and in its possible configuration [2].

Thus, the design and development of both the architecture for simplifying of development of such systems and the advanced diagnostics, monitoring and human-interaction will provide easy maintenance and increase the acceptance of such systems by providing the transparent insights into the functionality of its control part. Within the frame of this paper a potential approach – currently in the early conceptual phase – for improved the industrial acceptance and use of modern control systems for reconfigurable manufacturing systems is given.

The paper is organized as follows: section 2 provides an overview of the state of the art in the agent-based control and describes the problem statement. A possible approach to overcome the shortcomings in the agent-based control is given in section 3. The summary and conclusions are provided in section 4.

2 State of the Art and Problem Statement in Multi-agent Control

The multi-agent control approach is widely used for developing and designing the adaptive, reconfigurable, and modular structured manufacturing systems, which allow machines and plants to flexibly adapt themselves to the changing demands and interact with each other to fulfill the overall production goals. It is already well known as a naturally suited technology for designing and implementing of dynamic and intelligent production systems [3]. To achieve a quick reconfiguration of manufacturing systems and to avoid a time- and work-intensive reprogramming, the use of the Plug & Play approach in multi-agent architectures is desirable [4]. For most of the existing multi-agent architectures a modular representation of production system components is the first effort in order to achieve this goal. Coalition Based Approach for Shop-floor Agility (COBASA) [5] and Actor-based Assembly Systems (ABAS) [6] can be named as examples for such a modular negotiation-based multi-agent architecture. A holonic approach, applied in ADACOR [7], PROSA [8] and MAST [9], are another approved architectures for intelligent manufacturing systems where a holon or holonic agent is a representation of a manufacturing component.

Tichý et al. present the Autonomous Cooperative System (ACS) architecture targeted to distributed industrial control applications [10]. The main aim is to integrate the low-level control ensuring the real-time responsiveness and the intelligent agents featuring more sophisticated algorithms for planning, communication and diagnostics. The common PLCs (Programmable Logical Controllers) provide the hardware infrastructure for running both the PLC programs (mainly ladder logic based) and the C++ agents in a parallel fashion. Important aspect to mention in the context of this paper is that each agent contains a Diagnostic Module, which task is to monitor the health of the attached hardware equipment. If the Diagnostic Module detects a failure of the equipment, the agent starts to negotiate with other agents about reconfiguring the control system such as the alternative solution utilizing redundant resources is provided.

In all of these modular multi-agent control systems the agents' information processing and reasoning are "hard-coded" in the agents' behaviors. The application of ontologies for knowledge representation, sharing and high-level reasoning can be seen as the next major step ahead towards flexibility in the agent-based control systems [11]. The ontologies are necessary to enable knowledge driven configuration and reconfiguration in an extensible manner. One of the first attempts to utilize ontologies in multi-agent systems for manufacturing is the work done by Obitko and Mařík [12]. It is pointed out that the usual approach, when manufacturing ontologies are expressed in XML/DTD and the semantics is described only informally in a natural language, is not sufficient. It is necessary to have the formal description of the domain of interest that would be understandable to computer agents. These authors argue for utilizing Web Ontology Language (OWL) for expressing semantics and provide an ontology example from the transportation domain together with the discussion on the possibilities of translations between different ontologies [13].

Other ontologies describing specific areas of manufacturing domain are for instance the OZONE ontology [14], the Enterprise Ontology [15], or the "Machine Shop Information Model" [16]. The MASON ontology could be seen as a draft of an overall ontology for the manufacturing domain [17].

Ontologies and knowledge bases utilizing shared ontologies can be used for (re-)configuring production systems instead of reprogramming agents or even the whole control systems in order to adapt a production to the new conditions. Such an ontology-based multi-agent system is implemented e.g. at the NovaFlex shop floor assembly domain of Intelligent Robotic Centre in UNINOVA, Lisbon [18]. In the frame of the EUREKA Factory E-RACE project (E-RACE, 2004), Web-space for decision-making support and design of reconfigurable assembly systems was developed based on knowledge domains. The examples of domains specified with ontologies are product, process, concept, and embodiment [19]. An ontology-driven multi-agent control architecture within the transportation domain based on simulation of an assembly process is presented in [20]. Also Evolvable Assembly System (EAS) referred in [21] describes an ontology-based multi-agent control concept for assembly based on finely granulated modules representing manufacturing components. The vision of EAS is that the system will be aware of its current capabilities and capacities by receiving the order from the user, and that it will be able to propose the modification or extension by plugging equipment modules available from different vendors [2]. The key aspects of deployment of semantics and ontologies in distributed manufacturing control system are summarized in [22].

Common for all above named architectures and approaches is that the problem of user acceptance and understanding of "intelligent" control systems in automation industry was not explicitly focused. But it seems to be one of the key issues developers of reconfigurable multi-agent based systems are faced with [23].

Rockwell Automation, Inc. was confronted with this problem during its agentification project aimed at the steel rod bar mill for BHP Billiton, Melbourne. In order to increase the machine utilization, the agent-based control system was developed for dynamic selection and configuration of production resources. However, due to the anxiety about possible wrong decisions of the multi-agent control system that could lead to damage of equipment or production loss, BHP Billiton decided not to use it for direct physical control. Instead, the agent control system provided on-line recommendations for resource configurations and control actions, while the final decision about their execution was left to the plant operator. Regardless of this policy, the agent system proved to work well in all test cases. BHP Billiton was also reluctant to use a new intelligent control system in production because of the lack of skilled personnel able to maintain such a system [24]. DaimlerChrysler's multi-agent project Production 2000+ faced the similar issues. This multi-agent system targeted to control a flexible and robust production system for large-volume power-train manufacturing, and has been tested by simulation utilizing real production data (e.g., processing times, real disturbance characteristics of existing production systems). In order to validate simulation test results, DaimlerChrysler installed this production system as a bypass to an existing large-volume manufacturing line for cylinder heads in its plant in Stuttgart-Untertürkheim (Germany) [25]. However, the test phase was aborted after about one year, because operators were overstrained with the new flexible production system and especially with the problem that they were not able to determine if the plant is working correctly or not.

In principle, there are many obstacles to widespread adoption of agent-based technology in industry [26], namely

- *thinking of engineers* who were educated to consider centralized approaches only;

- *risks* as the industry environment is afraid of emergent behavior of MAS without any central unit – there are no formal algorithms or procedures guaranteeing that the MAS systems would behave as desired;

- *costs* – the immediate costs of introducing of the agent-based technology are higher than in the "classical" systems;

- *vendor-centric view* – until the end-users are able to develop and maintain MAS by themselves in a straightforward way, these systems are accepted with very serious difficulties, the end-user wants to keep things under control and to understand the solutions fully.

3 Proposed Approach for an Improved Multi-agent Control System

In order to increase the industrial acceptance and use of multi-agent systems for adaptive reconfigurable production systems, we propose a twofold approach consisting of:

- a modular, knowledge-based multi-agent architecture for simplifying the development of multi-agent systems, and
- a diagnostic and user interaction infrastructure for improving the plant operator interaction.

In order to simplify the development of Multi-Agent System (MAS), in our ontology driven multi-agent architecture, the system modularity will achieve very fine granularity on all the considered levels – that means on functional, physical, and software implementation levels. In order to leverage the advantages of using a building block principle in modularly structured production systems, small physical components together with local intelligence are capable to build any system configuration and to modify it. Besides the plug-ability of physical manufacturing agent modules, the usability and rapid (re-)configuration of the system is also assured through the plug-ability of finely granular behavior modules at the reasoning level. The proposed knowledge-based MAS provides a very flexible cognitive architecture, where new behavior or new features of an agent can be assembled from such explicitly defined behavior modules using a building block principle. That means the fine module granularity is given at the level of physical components as well as at the reasoning level of agents. Therefore, besides the plug-ability of manufacturing agent modules, our framework provides quite a flexible cognitive architecture with a mechanism of explicitly defined behavior modules, enabling the plug-ability at all the architecture's level. The new behavior or new features of an agent can be assembled from such explicitly defined behavior modules.

In order to address the issues of low trust in multi-agent industrial control architectures and anxiety from unpredictable and unmanageable agent behavior, we propose an architecture, where the human operator acts as a part – an agent – of the multi-agent control system. A diagnostic system identifying the current system state and notifying on wrong system behavior is crucial for improving the confidence in multi-agent control systems [1, 2]. Human Machine Interface embodies agents that collect real-time data, diagnostic events and decisions of particular agents and make this information accessible to the human actor agents. Depending on the environment's requirements or diagnostic results, the meta-agents give a recommendation or direction to the operator and, vice versa, accept recommendations or decisions from the operator. The attention should be paid to possible dangerous states requiring operator's attention as well as to correction of possible dangerous or wrong decisions of the operator.

3.1 Modular Knowledge-Based Agent Architecture

A main issue of the existing multi-agent approaches is that although the overall multi-agent system is very modular and flexible, the specific agents themselves are monolithic and specially tailored for their purpose at hand. Also high skills of programming are required from developers in order to develop or to modify agents. Therefore we propose a generic modular agent architecture which can be configured for the given specific functionality of the agent (see Fig. 1).

The proposed agent architecture is based on a hybrid two-tier architecture, where the functional layer implements the basic functionality, and the reasoning layer serves for deliberation. On the functional layer, a limited set of behaviors defines how the functional layer reacts within the environment. It basically controls the sensors and actuators. Any change of sensor data may cause a reaction in this layer. This layer can be given low-level tasks by the reasoning layer. A default behavior, relying upon no perceptual information, is sanctioned if no other action is initiated. This causes the agent to continue accomplishing its current task. On this layer, it is also possible to accomplish certain simple goal-oriented steps such as to react to internal and external states.

The knowledge-base is a fundamental part of the agent as it captures the actual state of the surrounding environment as well as the agent itself in a semantic context. It means that the data the agent obtains by sensors or by communication with other agents are given semantic meaning by associating the facts with matching elements in the knowledge structure provided by the ontology. The important aspect is the reflectivity – the knowledge base representing the agent's data model of the reality contains the notion of itself, thus enabling the agent to reason about itself in the context of relations to other entities in the environment. Self-reflectivity achieved in this way, represents an important step towards higher autonomy of agents [27].

Let us have a simple example from the transportation domain. The ontology defines for instance classes representing a *conveyor*, *diverter* and relation *connectedTo*. In a particular scenario, the knowledge base of the conveyor belt agent *cb14*, which connects the diverter *d13* with the diverter *d15* contains an instance *cb14* of the conveyor class representing the agent itself and two instances *d13* and *d15* of the diverter class linked with the directed *connectedTo* relation to the instance *cb14*. This knowledge can be used by conveyor agent for reasoning about itself. For instance, when the diverter *d15* connected to the end of the conveyor sends a message about its failure, the conveyor agent updates its knowlege base with this new fact (by attaching failure label to object d15 in knowlege base). Then, following the *connectedTo* relation from *d15* to *cb14* (itself) the agent realizes that he is also affected by the failure and that an action is needed (e.g., to stop itself so that items currently on the conveyor are not fed to the failed diverter).

The novelty in this new agent architecture is how the knowledge-base is maintained and how it is integrated with the activities performed by the agent. The Behavior Management Component manages so called behavior modules that associate particular declarative knowledge with procedural knowledge representing the behavioral aspects of the agent. When a new fact is stored in the knowledge base the agent executes associated rule-based behavior as an action required to be taken as a response to new information. The proposed architecture allows to modify the behavior

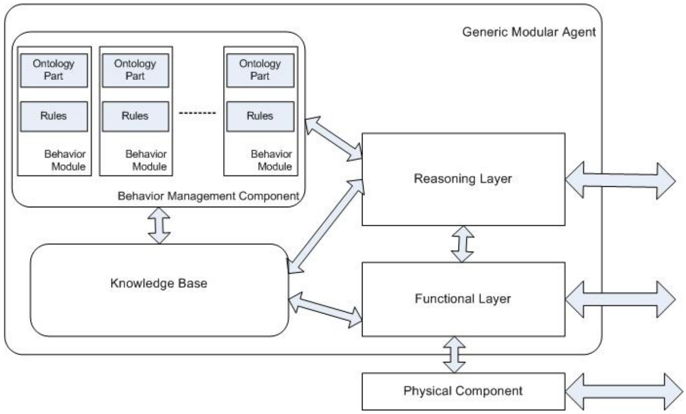

Fig. 1. Overview of the generic modular agent

modules of the agent on-line; the agent can receive new modules in order to extend or modify its knowledge, both declarative and procedural.

In general, many of the behavior modules will be standard components and only a small part has to be newly developed. Therefore, a basic set of behavior modules handling standard tasks of agents should be developed. Such standard tasks will be for example interaction with other agents, interaction with low level control, planning, scheduling, self-diagnostics, etc.

The proposed architecture of the generic agent can be seen as an extension of the acquaintance model architecture [28], which was widely used in ProPlanT and ExPlanTech family of production planning and scheduling systems [29], where the three knowledge bases contained the generic rules, the list of used rule instances and the database of plans/schedules, respectively.

The advantage of the approach presented in this paper is that the behaviors (consisting of generic rules, but also knowledge ontologies in addition) are represented by modular, functionally self-contained entities – building blocks – allowing simple assembling of specific behavior in a similar manner as the Lego™ blocks. Both the high degree of modularity and the application of ontologies do differentiate our solution from the acquaintance model approach. Due to this fact it is easier for the user to understand, to program, and, if needed, to manipulate such a single component than a whole complex algorithm of a typically programmed agent.

3.2 Diagnostic and User Interaction Infrastructure

In order to gain confidence in the new multi-agent technology among the managers and stakeholders in industry, it is necessary to design and develop an advanced diagnostic, monitoring and human-interaction system that would provide transparent insights into the functionality of the agent control system together with means for easy maintenance of such a system. An important factor to be considered is that the personnel that use these systems might not have any knowledge about the internal functionality of agents, their behaviors and decision-making, inter-agent negotiations, etc. Thus these "behind-the-scene" processes should stay hidden for the user; however, they must be translated into a format comprehensible to the user. This is an especially challenging task for agent-based systems where the reconfiguration of production processes occurs at first sight randomly and unpredictably. This is caused by the autonomy- and interaction-based character of agent systems, where any event (e.g., failure) diagnosed by one agent starts a cascade of messages sent among agents in order to take a corresponding action, either in a collaborative or competitive spirit.

We propose a general framework for providing clear explanations of the diagnosed events and consequent actions of the agent system. The framework is based on a hierarchy of meta-agents that monitor the activity of agents at particular level of the manufacturing enterprise and provide this information in a meaningful form to the user. At each hierarchical level, an appropriate knowledge bundle with relevant information granularity is provided to the user - from the highest ERP levels with overall business performance insights down to the real-time control level with the information for plant operators about which particular sensor notified the failure (see Fig. 2).

Beside the detection and correction of the failure, which has already occurred, the future production systems should be able to predict possible failure in order to act in a preventive way. That means the production system should be able not only to react to the failures such as collision, mechanical malfunction etc., but also meet the problem of wear-out and preventive maintenance. Such service requires permanent monitoring, analysis, and evaluation of the status of manufacturing resources and the whole production system as well as periodic reports to the users on different hierarchical levels. Due to this, service and predictive maintenance of the manufacturing resource or system can be accomplished not only in fixed time intervals, but earlier or later depending on the detected status of the manufacturing resource in a shop floor. That means the failure detection and correction should be performed both locally by the agents representing manufacturing resources, based on their local knowledge and

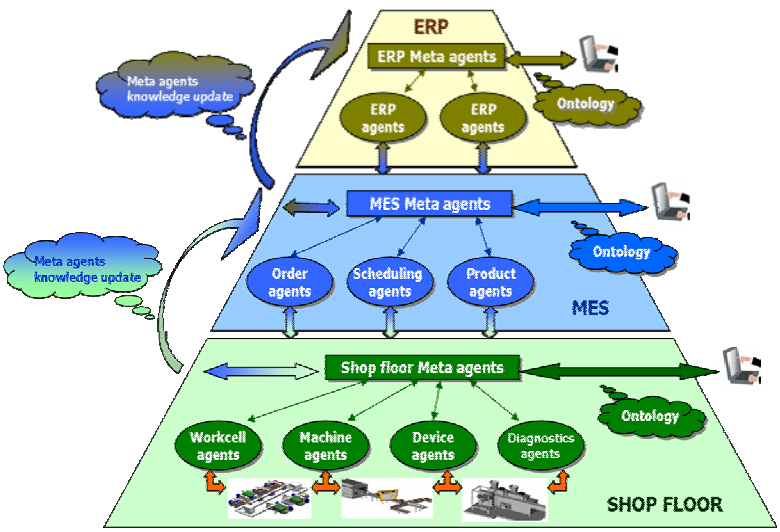

Fig. 2. Architecture of the diagnostic and user interaction infrastructure

information, as well as by agents representing production functions (such as the order or the supply) in a higher hierarchical level of the manufacturing enterprise, monitoring the possible failures emerged due to interaction of manufacturing resources. This is ensured by the cross-layer interaction between meta-gents as shown in Fig. 2.

Therefore each agent representing a certain manufacturing resource should be able to make diagnostic conclusions about its status, actions, behaviors etc. and to make its own decision if it is able to accomplish any correction of the diagnosed failure or not. That means the agent has to monitor itself and to reason about its state. In our generic modular agent architecture (see Fig. 1) this is the task of the reasoning layer. The agent knows its exact behavior in order to achieve its goal and to fulfill a given task. It compares the expected behavior with the observed behavior. If any discrepancy between the observed and expected behavior appears, the reasoning layer is expected to try to explain this discrepancy and to detect the possible failure. If possible, the reasoning layer starts to correct the failure; otherwise human intervention will be requested through the meta-gents at given layer. At the same time, the production system adapts itself to the new conditions by interacting and negotiating among its agents in order to maintain the production. If, for example, the malfunction of a conveyer is detected, the reasoning layer of the conveyer agent tries to explain and detect the failure (e.g., the malfunction of the conveyer motor). Contemporarily, the transport system adapts itself to the new conditions: the relevant pallets will be rerouted; an error report will be generated and sent to the Shop Floor meta-agent and the diagnostic agent. Depending on the severity of disturbance, the meta-agent decides to inform the operator about the disturbance immediately – asking for the operator's acknowledgement to start with error correction measures – or to postpone the provision of the information to a regular error summary report. If the conveyer agent comes to the conclusion that it is not able to repair the disturbance, it will contact its meta-gent and require human intervention. Also if the malfunction detected by an agent is unknown to him, the agent contacts the diagnostic agent at first, containing history of the disturbances and malfunctions in the system for some period of time, asking for help. The direct human user intervention will be requested only if the malfunction is also unknown to the diagnostic agent and the production system is incapable to solve the problem by itself. The same diagnostic principle [30] used by the agent representing a manufacturing resource can be applied to agents representing production functions on a higher hierarchical level of the manufacturing enterprise.

The goal is to have a diagnostic system that can achieve some attributes and abilities as named in [31]: early fault detection and diagnosis, ability to differentiate among different failures, robustness, ability to identify multiple faults, ability to provide explanations on how the fault originated and propagated to the current situation, adaptability, ability to decide, whether the process is normal or abnormal and if abnormal, whether the cause is a known malfunction or an unknown, novel malfunction, etc.

The fact that in our ontology-driven MAS the manufacturing system is represented by a combination of agents representing all production participants, allows the human user to interact with a system at appropriate level of manufacturing enterprise, to get or provide the information needed or to intervene if required. Information and knowledge exchange among meta-agents and users is based on application of a modular ontology providing unambiguous semantic interpretation of states, events and actions occurring in the production system. Based on the login data of the user the meta-agent of particular level of manufacturing enterprise will be contacted. The interaction, information and knowledge exchange between the user and the meta-agent do depend on user's access authority. So, any deeper understanding of the complexity and functionality on all levels of the underlying system is not required. The meta-agent provides relevant knowledge and information to the user.

The Human Machine Interface design in terms of Graphical User Interface in order to increase the user-friendliness of high intelligent manufacturing system is another important issue. As a paradigm, the experience and principles of Usage-Centered Design [32] or User-Centered Design [33] can be used and applied.

4 Summary and Conclusions

The current industrial agent-based solutions suffer from their quite low acceptance on different management levels of companies: the low acceptance can be seen by the company management, engineering community, and operators. There are many reasons for it, namely lack of "distributed thinking", increased investment costs and risks connected with such solutions [26]. In order to increase the industrial acceptance and use of multi-agent systems for adaptive reconfigurable production systems, we have proposed a multi-agent solution based on a modular, knowledge-based architecture of individual agents. This architecture stresses the autonomy of the agents and efficient and friendly communication with the users. Highly modular internal agent's structure exploring knowledge ontologies provides basic diagnostic features inherently and contains a user interaction subsystem for simplifying the development and enhancing the plant operator interaction.

The modularity of the proposed architecture is aimed at modular composition of models of agent´s behavior, capabilities of self-reflection [27] and enhancing the agent´s performance by making use of semantics and knowledge ontologies.

Through our modular knowledge-based agent architecture, the control engineer can more efficiently assemble the needed agent's behavior. Furthermore, the proposed architecture provides an efficient support for reconfiguring agent behaviors. It is able to foresee also several levels of diagnostic conclusions and different kinds of knowledge and facilitates the user interaction. Integrating our agent-based diagnostic approach and appropriate Human Machine Interface, the plant operator is expected to be able to interact better with the control system and more thoroughly understand the system's state. This will increase the operator oversight of the plant and greatly reduce wrong operator interactions.

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