METHODS FOR ANALYSIS OF THE TIME ASPECT IN THE BEHAVIOR OF AGENT-BASED MATERIAL FLOW CONTROLS

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ABSTRACT
The novel material flow control concepts like Internet of Things combine the up-to-date auto-identification methods with the modern software technologies. The expected control systems exhibit distributed scalable and flexible structures of stand-alone control entities. The price for these advantages is a non-deterministic time behavior of the local controls. The present study is devoted to the analysis of decentralized material flow controls under time constraints. The study results in a new approach to deal with deterministic and non-deterministic time factors. The paper introduces the Real-Time Logistics Model for identification, description and unification of time factors in conveyor systems and their controls. The model is integrated in and used with self-developed emulation software. The interplay of the model, the emulator and the agent-based control is shown in a real world example.

Keywords: real-time, software agents, internet of things, emulation

1. INTRODUCTION AND BACKGROUND
One of the actual trends in modern facility logistics is a modularization of the mechanical components with a simultaneous distribution of the control function (Wilke 2008; Hallenborg, Demazeau 2006; Bussmann, Jennings and Wooldridge 2004). This new approach leads to dissolving the hierarchical control structure with the material flow control (MFC) on top. The desired control system features a distributed flat structure of stand-alone control entities (Figure 1).

Various research projects accompanied by pilot implementations show the first steps toward the depicted goal (ten Hompel, Sondhof, Libert 2005; Bussmann, Schilz 2001). The research program Internet of Things (IoT) funded by the German Federal Ministry of Education and Research focuses on decentralized material flow systems too (www.internet-of-things.net). It combines the up-to-date auto-identification methods like radio frequency identification (RFID) with the modern software technologies like agent systems (ten Hompel, et al. 2007). In collaboration with German logistic enterprises several test-bed systems based on real world scenarios are currently under construction. A large-scale simulation experiment showed the advantages of the IoT (Roidl, Follert, 2008). In these scenarios the multiple software agents represent all essential elements of the conveyor facility like powered conveyors, junctions and merges but also the transported goods.

Figure 1: From hierarchical to mesh-like structure

The analysis of the agent-based control system behavior under time constraints is the object of study in the sub-project C5 “Realtime Logistics” of the Collaborative Research Centre 696 at the TU Dortmund University (www.sfb696.uni-dortmund.de). This paper presents individual results of this work.

The paper is organized as follows: We start with the topics which motivated our current research, then we specify the problem and set our research goals. In the next step we propose the system design including an abstract description model for time factors as well as the integration of this model into an emulation tool. Further, a realization and experiments are pictured on a real world example. In conclusion, we discuss the results and our further research steps.
2. MOTIVATION, PROBLEM DEFINITION AND GOALS

The agent-based control systems show a high level of scalability, extensibility and robustness. However, the price for these advantages is an autonomous and, as a result, a non-deterministic behavior of the individual agents and also of the whole system (Windt, Böse, and Philipp 2007). Particularly, the decisions close to the process must be always completed on time. Otherwise, the transport function cannot be fulfilled error-free and the control system malfunctions. Therefore, the impact of the time factor on the system control behavior must be known by developing high dynamic systems such as automated material flow systems.

Developers and operators of such systems need methods for analysis and planning of agent-based material flow controls with particular attention given to time constraints. Thus, a tool-supported method is required which allows to check the time-critical areas already in the planning phase and avoid or handle time-limits in the control realization. The expected benefit of this method is the reduction of the test and start-up time.

2.1. The real-time problem in the conveyor facility

The material flow is a real-time process. It consists of more than one parallel sub-process, exchanging the material, energy and information. Following the well-known dual principle, at least the same number of computation processes is needed to control such a system. Getting and setting the process data as well as the data computation, and even the synchronization of the computation processes, take some time. This time (\( t_{\text{control}} \)) must be shorter the higher the system dynamics is. Hence, the system dynamics define the maximal available time (\( t_{\text{process}} \)) for the control acting within one control cycle. This available time depends on some technical factors like number, performance and location of the installed sensor and actuator devices. Thus, for realizing the real-time capable control systems the following condition must be fulfilled (we purposely ignore the difference between the soft and hard real-time).

\[
 t_{\text{process}} \geq t_{\text{control}} \quad (1)
\]

To fulfill this restriction fast programmable logic controllers (PLC) are usually used in automation practice. These controllers process all time-critical tasks within a time constant computation loop. The division of tasks into the time-critical and not time-critical and also the distribution of control tasks to the PLCs are experience-based activities. Another experience-based and very laborious activity is the adjustment of sensor positions along the conveyor belt. The best practice for solution of this problem does not exist. A reasonable workaround for this problem is to use an emulation model for the detailed analysis of the system behaviour.

2.2. Specifics of decentralized MFC

The main idea of the decentralized material flow controls is the distribution of the control function along the facility. That aims at the reduction of the decision complexity. Depending on the desired level of decentralization the distributed software components (e.g. software agents) can run on their own hardware, close to the technical process. They assume a part of the time-critical tasks and, therefore, must act under the time constraint (1).

The essential distinction of this concept from the hierarchical control systems is the information uncertainty. Indeed, the centralized systems hold all the necessary process and topology information while the autonomous agents must be communicating with each other in order to collect and synchronize the information.

![Figure 2: Example of distributed decision making under the time constraint](image)

Figure 2 explains this problem at a simple example. A transport good (represented by an agent) approaches a switching area (represented by another agent). After the identification, the decision on the driving direction must be coordinated between the agents. For this purpose, the update of the routing information should possibly be performed as well as several other actions (e.g. writing some data on an RFID-tag).

The maximal available decision time corresponds to the journey time between the identification point and the switch trigger. It depends on the distance and the conveyor belt speed between these two points. A very short distance or too high a belt speed can result in the control malfunction. On the other hand, increasing the distance or reducing the belt speed results in the decrease of the system performance.

2.3. Methodological approach as a research goal

There are two practical methods to investigate the control behavior under time constraints: the direct measurement and the measurement by means of an emulation model. However, working with the emulation model is less labour-intensive and therefore preferred.

Unfortunately, the industrial emulator tools are developed to be used with PLCs and usually cannot be applied with agent-based systems implemented in a
high level language. Moreover, there is a method required to analyze the dependency between the control decision time and the process time. This method is necessary for both choosing the control performance, and setting and adjusting the influential technical parameters.

Most of the related works dealing with the time aspect of industrial control systems analyze the latency and performance of certain automation components and field devices like field bus systems, controller or RFID-Scanner (Tovar, Vasques 1999; Lian, Moyne, and Tilbury 1999). The developers of the real-time agent-based applications propose another approach. They consider the time constraint as a part of the agent program (Zhang 2006; De A. Urbano, Wagner, Gohner, et al. 2004). The agent must then complete all its activity when the available time is expired.

In our approach, we try to combine the advantages of both points of view. We propose a description model which unifies and consolidates the essential heterogeneous time factors. The factor values can be collected independently and put into the model. The model is integrated into emulator software which supports configuration and provides visualization of the model. Moreover, the emulator provides an open interface concept to connect an agent-based material flow control.

3. SYSTEM DESIGN

The proposed method design includes two parts. On the one hand, the conceptual model for heterogeneous time factors must be developed. This model has to combine the facility topology, the relevant process properties and the parameters of the control hard- and software. On the other hand, emulator software is needed which integrates the conceptual model and matches the process events and control commands to the time factors from the model. In the following, we describe the design of such a system step by step.

3.1. Material flow graph

The material flow graph is a directed graph which represents the system layout (see Figure 3). The graph edges model the powered conveyor lines. The vertexes display the transitions between two lines or crossing points. In this case, a conveyor switch can be modelled as a vertex with one incoming and two outgoing edges, a merge – vice versa. The vertexes without incoming edges are system entries. The vertexes without outgoing edges are exits.

Such a material flow graph can be used for calculation of valid routes through the conveyor system. The relevant physical characteristics of certain conveyor lines, like the line length, the transportation speed or the current load, shape the parameter set of the corresponding edge. Based on these parameters, the transportation time through the system but also along any single conveyor line can be defined.

![Figure 3: Example of the material flow graph](image)

### Table 1: Overview of time providers

<table>
<thead>
<tr>
<th>Time Provider</th>
<th>Process/Conveyor</th>
<th>(Process) Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available</td>
<td>Lead time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transition time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waiting time</td>
<td></td>
</tr>
</tbody>
</table>

The other category of time factors includes factors depending on the operation of control devices and control logics (Table 2). These factors are the latency of sensors (e.g. RFID-Scanner), delay on communication medium, data processing time and reaction delay (e.g. actuator switching, data writing). We call these factors time_consumers because they account for the available process time.

### Table 2: Overview of time consumers

<table>
<thead>
<tr>
<th>Time Consumer</th>
<th>Control Devices</th>
<th>Control Logic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data collection</td>
<td>Read time</td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td>Medium access time</td>
<td>Communication time</td>
</tr>
<tr>
<td>Data processing</td>
<td>Sync., cycle time</td>
<td>Decision time</td>
</tr>
<tr>
<td>Reaction</td>
<td>Write time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Action time</td>
<td></td>
</tr>
</tbody>
</table>

The maximal value estimation for most of the time consumers can be gained from device data sheets (e.g. sensor latency). The others can be calculated (e.g. medium access time) or be measured. These factors can be considered as static factors only depending on the device configuration and performance. The time consumers of the control logic involve such static components but also a dynamic part. For the dynamic factors the measurement in the operation mode is the only appropriate analysis method.
3.3. The Real-Time Logistics Model

In the Real-Time Logistics Model (RTL-Model) we combine the identified time _providers (tp) and time _consumers (tc) with the material flow graph. Every conveyor line gets a corresponding time _provider which describes the conveyor transportation time discussed above. The worst case for the control corresponds to the minimal transportation time, i.e. the situation when the transportation good is moving through the conveyor without stopping. Then, the requirement for the real-time behavior of the responsible local control unit can be written as follows:

\[
 tp_i \geq \sum_{m=1}^{M} tc_{i,m} .
\] (2)

Hence, the time _provider defines the maximal width of the time window for all static and dynamic time _consumers available for the corresponding conveyor and concerning its control. The time _consumers are characterized by two parameters: the value and the position on the conveyor line.

The graph representation of the system topology is not quite suitable for displaying the time factors of the RTL-Model. Therefore, we propose some graphical concept for the visualization of the RTL-Model. The time _provider is pictured as a segment of a circle over the graph edge (conveyor line). The length of the circle arc indicates the value of the time _provider. We can model the varying transportation speed via just adjusting the arc length. The time _consumers are displayed as sectors. The sector arc length corresponds to the value of the particular time _consumers. Thus a dynamic factor can be visualized just by varying the sector size. Different kind of time factors can be distinguished by using different colours.

![Figure 4: Dependency between time factors in the RTL-Model](image_url)

In figure 4 the visualization concept of the RTL-Model is explained by a simple example. An optical sensor at the beginning of the conveyor detects a packet (t1) and an identification device (e.g. RFID-Scanner) starts to read the data from the tag (t2). \(t_{\text{logic}}\) is the time needed for decision making. This time is a dynamical factor in the case of an asynchronous data processing. Similar to the previous example (Figure 2) the decision must be made before the sensor of the switching device (e.g. deflector) is triggered (t4). The deflector is set at the time \(t_5\) and the packet leaves the conveyor at the time \(t_6\). The time reserves describe the still available time windows. We attach the time reserves \(tr\) to the real-time constrain (2) to get the description for the conveyor time behavior without gaps (3).

\[
 tp_i = \sum_{m=1}^{M} tc_{i,m} + \sum_{k=1}^{K} tr_{i,k}
\] (3)

The next reasonable step is the integration of the RTL-Model into an emulator environment. The aim of this integration is to realize a computer-aided visualization and analysis of time related behavior of a decentralized material flow control.

3.4. Software integration

Most of the simulation software for material flow systems, currently available on the market (e.g. Arena, eM-Plant, AutoMOD), are oriented toward the centralized control structures and strategies. Connecting a decentralized agent-based control to such simulators is a big challenge because of missing interfaces. Furthermore, the emulators are used to work directly with PLC via OLE for Process Control (OPC) and field buses. The appropriate interfaces for high-level languages like C++, C# or Java are very rare. Moreover, the RTL-Model must be deeply integrated into the emulation software to catch and analyze both the events from the emulated facility model and the commands from the agent control.

![Figure 5: Overview of the emulator integration layers](image_url)

To gain more flexibility for our experiments, the RTL-Model was integrated into self-developed emulator software. However, the integration into industrial emulation software (e.g. Demo3D, taraVRcontrol) is feasible as well.

Figure 5 shows the layered architecture of the emulator. The time-discrete emulation core provides the other components with the clock pulse. The system layout representation is based on the material flow graph. Different layout models can be easily imported and used within the emulator. In addition to the layout
information, the emulated facility model includes information about automation components like sensors and actuators.

The layered system architecture enables integration of user-defined components, listening to emulator events or having connection to the superior material flow control. The RTL-Model is integrated as one such layer. The RTL-Model enhances the given material flow graph representation with its own elements: sensor and actuator information. The visualization layer provides a computer animation. It also allows for the editing and customization of the time factors in the RTL-Model. Finally, the pictured agent connector provides an interface to the agent-based material flow control.

4. EXPERIMENTAL ENVIRONMENT
In the following, the experimental set-up and the major system components are briefly pictured. Our experiment is not focused on the detailed study of the real-time behavior of the agent-based control. In fact, we use this experimental environment to show the interplay of the proposed method with a real agent-based material flow control.

4.1. Agent-based control
The control system is implemented using the JADE Framework (Java Agent DEvelopment Framework, see http://jade.tilab.com). There are three types of control agents in the system:

- The unit load agents represent the small load carriers. The synchronization between the software agents and the real boxes is based on RFID. The RFID-tags are used for both the identification and storage of transport relevant information.
- The conveyor agents represent the single sections of the conveyor facility with different transport function (e.g. switches, merges, buffer areas).
- A few service agents realize interfaces and general purpose functions like order management or an interface to a third-party system.

The JADE environment allows for an arbitrary distribution of the control agents on the run-time hardware. The self-developed event-based linking mechanism enables the connection of the agent system to the real facility the same way as to an emulated material flow system.

4.2. Real world test bed
The facility we use to test the real-time behavior of the agent-based control is a compact picking cell installation, situated at the Fraunhofer Institute for Material Flow and Logistics (IML). The system adjoins an automated small-parts warehouse at the system entry and an automated guided vehicle system at the system exit (Figure 6).

4.3. Using large-scale industrial models
The emulator software works with the internal conveyor facility models. However, it is also able to import and use a large-scale industry simulation models from AutoMOD, one of the leading simulation software on the market. One of the realized test scenarios includes the model of a legacy baggage handling system. The emulated model consists of approximately 12,000 conveyors and includes about 100 source-destination

The field control is a very simple program running on several embedded PCs. This program passes through the sensor events to the corresponding conveyor agents and translates the transport commands to electrical signals for actuator and drives.

The data interchange, which is close to the process, always depends on used automation devices and is often based on proprietary communication protocols. That is why we developed a hardware abstraction layer (HAL) connecting the agent-based control to the field control. The same HAL is used to link the control agents to the emulator.

Figure 6: Bird's eye view of the test-bed

The RTL-Model of the given facility is needed for the analysis of the time consumption of implemented decentralized algorithms. Figure 7 exhibits the extension of the emulator model to the RTL-Model. Here, most of the significant hardware Depending time factors are already included. The static time factor values are gained from data sheets or measured directly. The dynamic time factors of the distributed control logic can be measured and analyzed for the particular decentralized algorithms and test scenarios.

Figure 7: Emulation layout and the RTL-Model (overhead) of the test-bed

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relations. In this experiment the emulator was able to process the material flow events and send these out through the agent connection interface. However, for the practical usage of such models for our purpose the models must feature the corresponding level of details (sensor and actuator data).

5. CONCLUSION AND FUTURE WORK
The presented method to analyze the time behavior of conveyor systems and their controls consists of two major steps. In the first step, the significant time factors should be defined by means of the RTL-Model. In the second step, the simulation-based time measurement is fulfilled and then conclusions about the control quality can be drawn. The self-developed emulator tool integrates the support for both steps. The emulation software provides an easy-to-use linking mechanism to connect the distributed control systems, e.g. agent-based controls. The suggested computer-based analysis method can be used for an early recognition of likely bottlenecks and points of failure, possibly in the planning phase. Furthermore, it can be applied for both research and industrial purposes.

The discussed results provide the first steps in our research. The subsequent work supposes a specification of the RTL-Model for typical hardware installations and scenarios. The integration of the model into industrial emulators is another possible working step. The final research goal is the development of a methodology which allows for a comprehensive analysis of system performance under time constraints and save the development costs. The aspired vision is the realization of high-performance scalable material flow systems based on low cost control components and simple control logic.

REFERENCES

AUTHORS BIOGRAPHY
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