A SYSTEM-ARCHITECTURE FOR ROBOTIC MOVEMENTS OF GOODS

Approaches Towards a Cognitive Material Flow System

Dennis Ommen, Carsten Beth, Jens Kamenik
OFFIS Institute for Information Technology, Escherweg 2, Oldenburg, Germany

Axel Hahn
Department of Computing Science, Carl von Ossietzky University, Ammerländer Heerstrasse 114-118, Oldenburg, Germany

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Abstract: Flexibility, throughput, maintainability, scalability, reliability and low cost: That are the main optimization criteria of material flow systems (MFS). The most of this criteria are diametrical and so hardly to improve considerably with today's existing transportation devices and their static control structures. Hence a new approach of a transportation systems with cooperating robotic units and a novel cognitive environment will be presented. This approach will combine different research areas like robotics and wireless sensor networks to achieve a higher degree of flexibility.

1 INTRODUCTION

This paper will discuss aspects that will lead to a novel, cognitive material flow system (MFS). These aspects are: modularity, energy consumption, dynamic sensor integration, and computational architecture.

A few years ago carrying speed and throughput were the main performance metrics in MFSs. In the future properties like flexibility, modularity, reconfigurability and redundancy will play a decisive role. Reasons are the growing number of different products and product variants and thereon shorter product life-cycle and the growing complexity of products and processes. At the same time the product quality shall by high, the price low and the delivery time short. The movements of goods in a transfer station thus have to be organized in a flexible manner to fulfill these partly conflicting requirements with minimal stock of inventory.

Nowadays it isn't possible anymore to build a MFS for a transfer station which will last for 10 years or longer without being rebuilt substantially. In the future a MFS has to be reconfigurable by design, it must be possible to change the layout with a small amount of time and cost to be able to react on changing requirements (Windth, 2006). The static control structure of former systems has proved to be too inflexible. Therefore a new dynamic control approach an a new robotic system is needed to overcome these issues.

To build such new systems it has to be investigated (1) how to modularize the transportation system and how to identify the modules of single transportation unit (horizontal/vertical actuators, energy supply, controller, communication, etc.), (2) how these modules can be enabled to automatically acting as single transportation units, (3) how the different transportation units can cooperate with each other by using agent-based technologies to achieve a common purpose, (4) how to integrate all the necessary sensor information into a cognitive environment.

Paper Organization. The remainder of the paper is organized as follows: Section 2 introduces the new approach of a cognitive MFS. Section 3 discusses the related work and will show a research trend. Section 4 presents the cognitive MFS approach. The sections 5 and 6 highlights the systems requirements and also approaches towards a cognitive MFS. Section 7 presents concluding remarks.

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2 APPROACH

A cognitive MFS is characterized by (1) strict modularization where all modules are able to take individual, autonomous decisions of there acting, (2) cooperation of the modules in order to form a larger entity and/or to perform tasks collectively, (3) the incorporation of the environment in form of intelligent sensors, (4) dynamic reconfigurability of the system through adding, removing or rearrangement of modules, (5) goods accompanied by intelligent SW components cooperating with the before-mentioned entities in order to reach their destination.

The approach of decentralized cooperating autonomous logistic units, where goods and the transportation system autonomously make decisions, can be a way to realize the requirements drafted above (Scholz-Reiter et al., 2007b), (Scholz-Reiter et al., 2007a). Regarding where the decision is taken, the approaches can be separated into two clusters (1) good driven (Scholz-Reiter et al., 2006), (Scholz-Reiter et al., 2007a): An embedded device attached to the package escorts the goods to its destination. During the transportation process the embedded device cooperates with the environment to achieve its goal. (2) Transportation system driven: The environment around the goods takes the decisions. Here a possible process looks like that: With the arrival and identification of a good at the entry gate the environment creates autonomously the specific transport order that from now on escorts each autonomous transportation unit that handles these goods.

These autonomous transportation units are able to make their own decisions and to cooperate with each other. They can decide which transportation order they accept and how to deliver the good to the desired sink. Furthermore they achieve a high degree of freedom through the ability of cooperation with other units. To raises the degree of flexibility even more the transportation units consists of 1...n interchangeable modules. These modules are pluggable in vertical and horizontal direction to build an unique transportation unit. The abilities that these unique transportation unit now has, is derived from the currently used modules (Günthner et al., 2008b). The control paradigm of smart independent, autonomous transportation units shall lead to positive emergence with the promise to cope with the high dynamic of logistic systems (Windth, 2006). The main goals of such distributed systems are increased flexibility, carrying speed and throughput, increased maintainability, scalability and reliability through redundancy and decreased livecycle cost.

3 RELATED WORK

This section will provide an overview of the state of the art of robotic MFSs. It will not only focus on systems that are available on the free market but also on the current research. This paper will separate these products/projects into the following three categories: (1) central control and autonomous behavior: These MFSs are controlled via a central instance, where all the decisions regarding the transportations order are scheduled. These robotic systems are usually application specific and, hence there is no need for cooperation between the robots to fullfill a goal. (2) local control with autonomous behavior: Because of local control the presented system are scalable, flexible and failsafe. Thereon, the installation and reconfiguration costs are lower in comparison to central controlled systems. The robots act autonomously and don't cooperate. (3) local control with swarm behavior: robots cooperate with each other to achieve a common goal. This requires the ability to communicate with each other and to make local decisions.

Central Control with Autonomous Behaviour. The Kiva warehouse management system by Kiva Systems (Guizzo, 2008), (Wurman et al., 2008) is a commercial system for commissioning of products in stocks with small parts. The stock consists of many adjustable shelves with a matrix like structure on a flat ground. Small autonomous robots (Drive Units, DU) are able to drive under a shelf, lift it up and bring it autonomously to other locations, e.g. a picking station. Orders are accepted from a warehouse management system by a central computer (Job Manager, JM) which is responsible to schedule the DUs and picking stations as well as the shelf space at the station. After receiving a transportation request from the JM the DUs are responsible for their own task planning, path planning plus motions planning and control. Communication between the agents is done with XML messages at the higher level transmitted by wireless technologies. Because of the agent based architecture the system is highly scalable and can grow with the requirements, where the centralized Job Manager is a limiting part. A disadvantage is the limited field of application domains. The system is mainly useful for order picking processes that have a high degree on manual work.

Local Control with Autonomous Behaviour. Multishuttle is a product by Siemens Dematic AG developed together with Fraunhofer-Institute for Material Flow and Logistics in Dortmund,Germany. The modular system consists of autonomous vehicles driving rail-bounded inside of a warehouse system. The vehicles can drive at the horizontal direction and they can autonomously load and unload product carrier (at the same time). Rails are laid in several stacked levels. They take care for both - guiding the vehicles and energy delivery. Movement at the vertical direction is done by lifts. Transport orders are communicated to the vehicles by WLAN. The rail-bound energy delivery leads to a lower weight and price. But for the same reason the vehicles are bound to the warehouse, they can't deliver goods in the total area of the delivery station. In contrast to traditional warehouse systems like a shelf access equipment, the Multishuttle system is scalable. Thereon, the throughput be increased with some additional vehicles.

The system Servus form the Austrian company Servus Robotics (Servus Robotics, 2006), (Robotics, 2005) is intended for intra-logistics assembly automation. Like Multishuttle the system is rail bounded. The vehicles are able to act autonomously. They accept transportation orders through an infrared or WLAN interface. Additional information of the goods, like necessary processing steps, is stored at the vehicle. The goods themselves don't need to be intelligent. Additional actuators can be build upon the vehicles, e.g. to be able perform processing steps while the goods are carried. Energy is not supplied by the rail, unlike the Multishuttle, instead each vehicle has its own fast rechargeable energy supply.

Local Control with Swarm Behaviour. Another project investigating in robotic conveyers is the KARIS project of the Institute for Conveying Technology and Logistics (IFL) at the University of Karlsruhe, Gemany. They have presented a robotic transportation system (Baur et al., 2008), that consists of several homogeneous transportation units which are able to drive at the floor or stand at the floor while acting as a conveyer. The wheels thereby are turnable at 360 degrees providing free movement at the horizontal plane. A KARIS unit is able to carry payload by its own or if the charge is too large or too heavy, many KARIS units build a swarm and carry the payload together. If a large throughput is required several units can be combined to build a continuos conveyer with sorter function. Swarm building and acting is the actual research work at IFL.

The institute for Materials Handling, Material Flow, Logistics (IML) in Munich (Gemany) proposed a concept for future material handling systems (Günthner et al., 2008b), (Günthner et al., 2008a) consisting of low-scale autonomic transportation units. All transportation vehicles are small and have a simple and basic design causing a low price because of high volume production. For special roles they shall be able to be equipped with manipulators like a lift fork, roller or belt conveyer. They shall be autonomous with their own intelligence and communication options. If a task can't be achieved by a single vehicle, more of them shall form a swarm and act together.

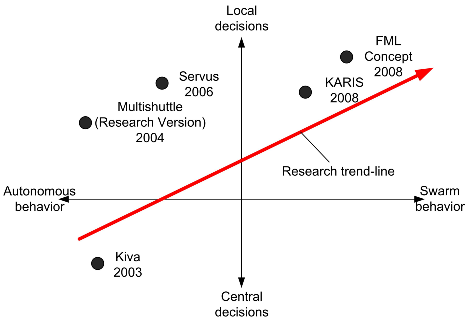

Figure 1: Trendline of robotic material flow systems.

Conclusion on the Related Work. As it is depicted in Figure 1 there is clear trend line towards autonomous robotic systems that can act in a swarm to achieve common goals in MFSs. The discussed research projects KARIS is an elaborated robotic system that shows that these systems can act in two ways: as a discontinuous or continuous conveyer. Nevertheless, this systems has no flexibility regarding the transported goods. The concept of the IML has this ability because of its changeable manipulators. Thereon, it can pickup different kinds of goods, like pallets and mixed cargo. But both approaches are limited to operate on the floor. In the following this paper will present an promising approach that self adapts to the transported goods and the layout of the transport area.

4 COGNITIVE MATERIAL FLOW SYSTEMS

A transfer station scenario with cognitive transportation units (CTU) is drafted in figure 2. Here the station consists of entrance and exit areas, a storing area and a working area between the entrance and the exit. Goods are delivered, e.g. by trucks at the ports of the entrance area. On the other side goods are removed at the ports of the exit area. The CTUs (red vehicles in the picture) are responsible for good transportation (goods are represented as pallets at the picture). According to the requirements CTUs can act as continuous conveyors or discontinuous conveyors equipped with different manipulation units depending on the kind of goods. In general the CTUs are modular. Because of the unified model it is possible to combine arbitrary modules in vertical and horizontal manner. Communication between the CTUs and the environmental sensors is done wireless. In figure 2 two types of communicating sensors are shown. The red one is a mobile sensor (CTU in its rule as a sensor); the green one is a fixed location sensor. The shown scenario raises some questions to the aspects of modularity, energy supply, sensor data delivery, dynamic sensor integration, and communication. These aspects are highlighted in the following sections.

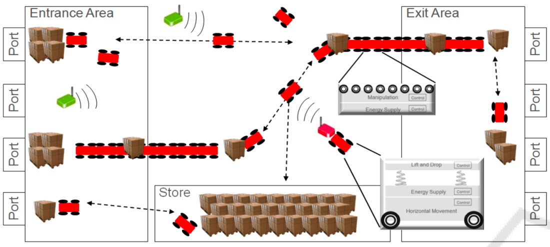

Figure 2: A cognitive material flow scenario.

5 COGNITIVE TRANSPORTATION UNIT

Modularization. As it has been stated in the previous section the CTU consists of modules that have different abilities. This key approach of modularization gives cognitive MFSs the flexibility to adapt not only to fluctuation in the load but also to adapt to different kind of goods that need to be transported. So needs a parcel an other manipulator as an mobile shelve. The decomposition of the CTU leads to the following kinds of modules: (1) A conveyer module for fast transportation of goods in horizontal direction. If many of this modules stands next to each other they can act like a continuous conveyer system. (2) an elevating module, for movements in vertical direction to lift or lowering goods. This module is needed, e.g. to transport an mobile shelve or to compensate difference in the height during the pick up process of a good. (3) A manipulator module can either work in combination with the conveyer module or with the elevating module to grab or release a good. To be able to handle different kind of goods, e.g. pallets or mobile stock, there should also different kind of manipulators. (4) A power supply unit, that energizes the system. Like the other modules this is also designed-for-purpose. So can the power supply unit be based on batteries or can even be a stationary power supply to support or load other CTUs. (5) The movement unit allow the CTU to act as an discontinuous conveyer system, with different kind of this modules the CTU are able to drive on the floor and also to drive into a stock.

Because the power supply is an mandatory on, there are at least 20 CTU combinations possible, which will leverage the MFS to respond in an even more flexible way. The modules can either be stacked vertical (on top of each other) , e.g. to build discontinuous CTU (with modules (1)-(5)) or horizontal to build a continuous CTU with module type (1). There should be no limitation regarding the used number of modules to build an CTU. The modularization requires new ways of communication, control and perception between the CTU modules and then between the CTUs themselves.

Towards a CTU System Architecture. The previously described modularization has also its impact on the computational architecture of the CTU. Here are different communication channels mandatory: (1) The vertical channel handles the communication between the modules of the CTU. This communication channel have hard criteria regarding the reliability of data transmission and real-time requirements, e.g. because of used closed control loops that set the speed of the CTU wheels. Thereon this channel is typically wired and represented by a field bus with high bandwidth, like CAN or Flexray. (2) A horizontal channel: This communication interface is used to interact with (a) other CTUs and (b) the cognitive environment, which is discussed in detail in the next section. A communication between the CTUs occurs, when goods need to be transfered between them or when transportation orders need to be negotiated or for swarm cooperation. The channel (2) with its different interfaces is a wireless one, that has to fulfill special requirements regarding energy optimization or real-time. Because of the numerous communication interfaces, that have divers API and physical characteristics, an abstraction layer is needed that makes the communication to the CTU modules and CTU itself transparent. This abstraction layer (middleware) has to support Quality of Service parameters that specify the fault tolerance or real-time level of the communication. Furthermore this Middleware has to support different embedded devices, that are used inside the CTU modules or the sensors from the cognitive environment. This can differ in used microprocessor architecture, e.g. from 8-Bits to 32-Bits architectures and their program storage size (flash-size).

Energy Efficiency. As stated in (Overmeyer et al., 2007) optimization under changing general conditions has still to be favorable for the overall logistic system. A battery is a limiting factor for the time t of useful work. The strategies the CTUs are using to fulfill a task directly influence the energy drain of the battery. For example, if the CTUs try to greedily minimize the waiting time criterion in (Overmeyer et al., 2007) they drive with the highest speed to the nearest source, catch a palette and drive with highest speed to the sink of the palette. If all CTUs choose this egoistic strategy they start to block each other because the most efficient path from the source to the sink is overused. At the end they may not be able to fulfill the task at all because the strategy is to energy consuming for the whole system. For this kind of system the optimization criteria has to be reformulated in a way considering energy consumption. A trade-off has to be found between the energy consumption and the application needs. As an example, for high prioritized costumers the focus lies on speed and energy is less considered and for low priority costumers energy is considered more. For the longest availability of the overall system a uniform distribution of energy might be useful. But, this optimization may lead to the fact that all CTUs have to recharge at the same time and the system is unavailable; an additional optimization criterion might then be that the mean number of recharging CTUs is e.g. not higher than 15% of all CTUs in the system. The following assumptions are made: Batteries recharging takes a significant long time. During this period the CTU is not able to do valuable work, e.g. it is unavailable. Three states characterize the (simplified) CTU: driving, turning and lifting. Every system state has characteristic power consumption at a time t and the overall system energy consumption at time t is:

$$E_{AutSys} = E_{Driving}(t) + E_{Turning}(t) + E_{Lifting}(t) \quad (1)$$

Additionally the power consumption depends on the load (kg), the speed $(\frac{m}{s})$ and acceleration $(\frac{m}{s^2})$ of the CTU. If the CTUs now receive a task they have to (1) choose a strategy for the task and (2) estimate the time they will spend in each system state, (3) calculate the overall energy for the chosen strategy and (4) compare the energy consumption with the given optimization criterion - if this is violated go back to (1). With this approach an energy optimized strategy for logistic systems can be found.

6 COGNITIVE ENVIRONMENTS

The basic cognitive capabilities are perception, reasoning, learning and planning. A cognitive environment consists of systems that show a similar strategic behavior like human individums do. For the modelling of cognitive human processes, e.g. cognitive systems, different architectures have been developed (Laird et al., 1987) (Anderson and Lebiere, 1998). In these architetures the perception (sensing) of the environment and the storage (memory) of sensor data are important basics for learning and reasoning. In former logistic systems like forklifts the only sensory information comes from the limited human perception. The same problem have autonomous logistic systems e.g. driver-less systems that rely on built-in sensor information. Their view of the environment is limited to the perception ability of the integrated sensors.

Sensor Abstraction. In the proposed transfer station scenario sensors are usable by everyone. This expands the view of the environment to the whole scenario. Every autonomous system is able to get this view to raise the correctness of their decisions. For example, in (Riedmaier, 2008) the only sensor information was the soil condition of the track. With only this information the speed of forklifts could be optimized and the handling of palettes could be increased about 5%. In the proposed transfer station scenario external sensors are attached to the walls able to detect movement of non-cooperative and cooperative systems. With the help of these sensors a CTU is able to drive with high speed towards an intersection where it otherwise would not be able to sense if another robot is crossing it and, therfore had to reduce the speed. To unify sensor communication wireless- and wired communication media have to be integrated into every sensor. So, every sensor can act as fixed external sensor or if necessary can be attached to an autonomous robot to improve their sensing capabilities. As the cognitive logistic system allows a task adapted flexible restructuring, fixed sensors are a problem. To allow flexibility, the CTUs are able to move the sensors to a new position. From the modeling point of view, sensors are agents running a sensing task for a long time. In the restructuring process of the logistic system they get a new task and autonomously decide if they can fulfill this task (1) with their sensing capabilities and (2) at their actual position. If (1) is not fulfilled they have to reject the task, if (2) is not fulfilled they can require help from an autonomous robot to replace them to a better position. Agents are the abstraction of the real embedded devices in the proposed cognitive logistic system and consequentially sensors are abstracted with agents as well - this unifies the whole transfer station scenario world view. Further usage of the network of sensors can be as a communication relay for the CTUs and sensors. Due to limited propagation of radio waves in logistic in-door facilities the assumption that all sensors can communicate with each other is not true. Therefore, using the multi-hop capability of modern wireless sensor networks is a good way to extend the range of the sensors and the CTU's communication system.

Sensor Data Memory. Sensor data is important for decision making of the control algorithms. Therefore, it needs to be protected from communication and sensor node failures. For industrial environments WirelessHART (HART Communication Foundation, 2007) is a standardized protocol for reliable wireless communication and can be used in the proposed transfer station scenario. It provides robust self-organizing and self healing mechanisms to encounter communication failures. But networked sensors have far more potential, in a cognitive system they can be used as distributed observers. A distributed observer is a sensor with its own memory that stores a snapshot of the past. It is similar to the human short-term memory (with low-capacity) and is used in many cognitive modelling architectures (Laird et al., 1987) (Anderson and Lebiere, 1998). This kind of sensors can answer questions about situations of a larger context, which is usful for coordination and optimization purposes. Distributed sensors have an area to observe. For example, a fixed sensor knows about the robot traffic in his area and can therefore give a usage estimation of the path belonging to his observation area. Technically, sensors now have to store their data instead of just sending real-time data to the CTUs. The CTUs then ask the sensors for certain events in their stored history snapshot. For fault-tolerance reasons, sensors are allowed to replicate their data to other fixed or mobile sensors. They can use different replication strategies to trade-off data availability for energy and vice versa.

7 CONCLUSIONS AND FUTURE WORK

Present state-of-the-art projects were considered as too domain specific and not able to raise the flexibility of logistic systems comprehensively. Therefore, this paper proposed modular principle that raises the flexibility of the system. Energy is an important factor for battery driven autonomous robots, therefore strategies for the trade-off between energy consumption and timelines were discussed. Furthermore, a unified sensor integration scheme was proposed that raises the cognitive perception ability of the whole logistic system and a sensor data concept that enables the idea of a distributed observer was shown. At the moment the proposed models are being implemented and in a next step they will be simulated. The goal of the simulation is to find the best granularity of the modularization and to find the best cooperating strategies for autonomous logistic systems. As a next step a test bed implementing figure 2 for validation of the chosen strategies will be created.

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