Concept of Cellular Transport Systems in Facility Logistics

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Abstract—The proposed concept of a Cellular Transport System shows the possibilities to increase the flexibility and changeability of facility logistics systems and enhances the ease of use of complex decentralized control systems. This contribution shows how to enhance these issues compared to conventional facility logistics systems, e.g. static conveyors, by using an autonomous vehicle swarm. Cellular Transport Systems are based on dedicated (cellular) material handling entities. Generally, these cells consist of autonomous transport vehicles (ATVs) or autonomous conveying modules. Various functions such as advanced sensor/actuator interoperation, highly reliable communication, localization and energy management are implemented in each of this cells, facilitating different forms of adaptive, anticipatory and collective behavior. Furthermore, Swarm Intelligence enables the creation of a collective that interacts and cooperates amongst each other in order to solve complex tasks.

Keywords—Cellular Transport System, Automated Guided Vehicle, Internet-of-Things, Swarm Intelligence, Multi-Agent System, Facility Logistics

I. INTRODUCTION

Productivity and flexibility are worldwide key challenges for industries and supply chains in terms of competitiveness and dynamics in global markets. Practical experience shows that highly structured industrial environments are very costly and time consuming in terms of changing or adapting such systems. Today no system meets the tremendous challenge of continuously changing requirements for facility logistics and is simultaneously able to increase the degree of automation, flexibility and changeability. During the last years, research activities in decentralized material flow control connected with the Internet-of-Things architecture in logistics have been growing (cp. [1], [2], [3]). The basic idea of these concepts is the distribution of the prevailing central controls to a multiplicity of smaller self-organizing decentralized control units. Decisions are made autonomously by the decentralized units based on local and probabilistic informations. Today, hierarchical structures are dissolved towards a mesh-like structure with self-containing entities. In material flow systems, these entities represent logistical objects: conveyors, unit loads or AutoID devices. Every entity acts autonomously and communicates with other entities. The communication between them is service-based. The holistic system function is then achieved through composition of different services from different entities. Encapsulation of construction and design together with the use of services as the systems interface ensures much higher flexibility. The entities are easily exchangeable and even replaceable by entities from different vendors. All previous Internet-of-Things projects were based on static conveyor systems in which unit loads are forced to use given ways and routes through the system. But the flexibility and autonomy is limited by the physical build-up of the conveyor system. The next step is the replacement of the conveyor system by a group of transport vehicles which are able to pick up unit loads and to have open path navigation. This so called Cellular Transport System is intended to overcome this trade-off by adding value to and by enhancing autonomy of sub-elements like Automated Guided Vehicles by the use of autonomous Software Agents [4] and Swarm Intelligence [5].

A Cellular Transport System is an application of Swarm Algorithms to control the autonomous vehicles’ behavior. Moreover, optimization can be attained by using Swarm Algorithms for localization, navigation, collision avoidance, task allocation and transportation tasks. With this capability of cooperation in a swarm, different transport units can be carried in a collective of vehicles. So the flexibility and performance in completion of transportation tasks is increased by using a swarm of vehicles for example by shared sensor information for predictive collision avoidance or interaction between the vehicles. As a main result, an entirely new degree of flexibility for designing logistical systems is achieved in terms of cost-efficiency and flexibility enabling a sustainable competitive advantage. An overview of this new system design will be given in the course of this paper.

II. CURRENT RESEARCH ACTIVITIES

Facility Logistics is a multi-disciplinary domain and benefits from several fields of expertise like Mathematics, Computer Science, Automation, Robotics and different Engineering disciplines etc. First, an overview of known state-of-the-art facility logistics systems that are based on groups of vehicles is given in this section. Afterwards, a selective overview of our methods to build-up a Cellular Transport System is described.

A. Applied Logistics

Currently, there are several approaches of replacing static conveyor systems by groups of vehicles. Subsequently, some popular realizations and concepts are mentioned:
1) **KIVA Systems**: The KIVA Systems solution consists of several or up to hundreds of robots capable of lifting and carrying shelving units in a warehouse [7]. The largest installation at the moment consists of 500 KIVA robots handling goods in a warehouse of STAPLES, USA [8]. The robots, called *driving pods*, use two cameras that read barcodes placed under the shelving units and on the floor as artificial landmarks for navigation. This information is combined with readings from other navigation sensors, such as encoders, accelerometers and gyroscopes. The robots have a grid-based guideline navigation. In addition to that translation and rotation movements cannot be done simultaneously. The maximum speed is limited to 1.3 m/s. The projects’ focus was on the development of a centralized multi-agent system that controls the robots.

2) **KARIS Project**: Within the KARIS project, a flexible material flow system is being developed at the Karlsruhe Institute of Technology (KIT) [10]. The system consists of several autonomous vehicles measuring half a square meter at a height of 40 cm and a roller conveyor mounted on top. These vehicles are capable of adapting themselves to continuous changing requirements by forming a compound in order to transport big loads as well as forming a conventional conveyor track for high throughputs. For these purposes they may locate themselves in a known environment using two laser rangefinders and communicate amongst each other via WiFi.

3) **ARMADA**: The Basic Intralogistic Element (*BInE*) represents an autonomous module that is able to transport small part containers as well as transporting a pallet with a cluster of four *BInEs* [11]. Due to a bi-directional drive mounted to the upper side of the module, several *BInEs* could be combined to form a continuous conveyor system. This prototypical system has been developed during the ARMARDA (Autonomous Reliable Material Handling Systems of Aggregated Redundant Distributed Actuators)-project. The main focus was on the mechanical construction and the formation control of these transport components disregarding sensor technology, energy supply and navigation strategies.

4) **ADAM AGV**: ADAM is an Automated Guided Vehicle manufactured by RMTRobotics in cooperation with MobileRobots [12]. It uses the open path navigation provided by MobilePlanner software of Mobile Robots. The maximum speed amounts 1.5 m/s. The ADAM solution affords a modular vehicle platform and does not provide any complete solution including a material handling device. Up to five ADAM AGVs build up a compound called "fleet". The fleet is controlled by a PC-based centralized software control system. Interaction between the robots is not part of the ADAM system.

5) **Multishuttle Move**: The Multishuttle Move (MSM) is a novel fusion of conventional shuttle and automated guided
vehicle systems developed by Fraunhofer Institute for Material Flow and Logistics. Like the Multishuttle Roaming [13], the new vehicle is rail-guided while it is located in the racking system or the lift. Furthermore, the Multishuttle Move is able to leave the rail-system and to operate as an AGV with open path navigation (the so called ATV). This navigation is based on Sensor Fusion of Round-trip Time-of-Flight ranging within a Wireless Sensor Network (WSN), measurements of two laser rangefinders and dead-reckoning. The MSM is provided with a differential drive which has a maximum speed of 1.1 m/s on the ground and 2.1 m/s in the rail-guided racking system - the higher velocity in the rail is realized by a gear. The maximum acceleration is limited to 2 m/s\(^2\). A single vehicle weighs no more than 134 kg, but can transport payloads as high as 40 kg. Through the mutual concept different load handling devices (LHD) can be assembled on the ATV - at this stage a telescope LHD, a belt conveyor for double cycle LHD (simultaneous loading and unloading) and a passive non-powered LHD. Additional vehicles can be added to the swarm even during runtime just as the reduction of the swarm size is also possible. The scalable and flexible vehicle swarm concept is a compact, adaptable solution for high storage capacity and covers the entire performance spectrum of facility logistics with the maximum possible flexibility.

B. Extract of Fields of Expertise

1) Cellular Transport Systems: According to definition, Cellular Transport Systems are based on material handling entities. These are autonomous transport vehicles or autonomous conveying modules. The control and the communication between these entities is done by Software Agents. Cellular Transport Systems are flexible in their topology and are able to adapt to environmental changes. Finally, this ensures the overall transport systems’ performance due the interaction between the material handling entities [14].

2) Swarm Intelligence: Swarm Intelligence in artificial systems composes many individuals that operate using decentralized control and self-organization. It focuses on the behavior of the collective, which results from the interactions of the individuals with each other and with their environment. Like in natural swarms (e.g. fish swarm) no central entity is needed for the coordination of the individuals, so task organization and task allocation can be managed decentralized [5].

3) Sensor Fusion: The main purpose of Sensor Fusion is to achieve more precise measurements based on probabilistic approaches with several sensors than by particular evaluation of the sensors. So Sensor Fusion enables the reduction of sensors or the improvement of the measurement accuracy. It can be accomplished by Fuzzy Logic, Kalman, Extended Kalman, Particle Filter algorithms. Usually a sensor model is used for this purpose - especially for predictive algorithms [15]. Eventually, Sensor Fusion Algorithms can be used for localization, collision avoidance and classification in the Cellular Transport Systems.

4) Software Agents: The main objective of multi-agent systems is to control complex systems without a central entity. These systems employ a set of agents that are autonomous, proactive, adaptive, and reactive. Software Agents own special competences to solve problems, acquire information, prevent conflicts, etc. and are able to interact with other agents to solve the global problem [4].

III. SYSTEM ARCHITECTURE

Our approach to an adaptable, flexible and scalable ATV is the Multishuttle Move whose architecture and technical basics are described in the following sections.
sensor data acquisition and the closed-loop drive control for vehicle positioning. All safety relevant tasks (target: Performance Level d according to EN ISO 13849 and SIL2 according to IEC 61508) are also located in this layer and operate decoupled from the rest of the control system to meet the safety requirements. The tasks are executed in a software programmable logic controller (Soft-PLC), which is running on the industrial PC parallel to the embedded Operating System.

The operational layer is responsible for mid-term tasks, like collision avoidance, localization and path planning. The collision avoidance identifies possible obstacles with the help of the sensor data from the SA layer and initiates a replanning of the actual path or a reduction of the velocity depending on the actual situation. The ATV state task is responsible for acquiring and analyzing vehicle data from the operational and SA layer, making this information available for the strategical layer or even external systems. Information of interest are the current state of charge, the actual position and velocity of the vehicle or the load condition. All tasks of this layer run as threads in the vehicle operating system.

The strategical layer at the top is responsible for long-term operation and planning. The objective of this layer is the creation of an autonomous behavior, which is realized via Software Agents. Therefore every vehicle is represented by a Software Agent, which is able to communicate and interact with other agents and external systems, like job management. The Software Agent has a communication interface to all tasks of the operational layer. The connection to the SA layer is done via the ATV state task. The task autonomous behavior runs, like the operational layer tasks, in the vehicle Operating System.

The intrasystem connection between the three layers is realized via UDP socket communication (cf. section III-B). The communication to external systems and other ATVs is done via radio frequency technology under use of TCP sockets. An example for interaction of all three internal layers and the external layer is outlined in the following scenario: Through the job management, the autonomous behavior task of one ATV gets information about an unit load, which needs to be transported. The task starts the routing based on the current position of the ATV and source-sink relations. The planning results are one or more destination and navigation-support points. These points are transferred to the path planning task (operational layer), which plans the trajectory and pose of the vehicle. The results of path planning are transferred into commands for position control (SA layer). The position control then generates control values for the drives of the ATV. This scenario shows how the MSM system represents the autonomous and decentralized concept of the Internet-of-Things architecture and the Cellular Transport System (cf. section I).

B. Technical Realization

The ATV integrates all of the addressed functions: sensing, actuating and communication. Smart sensors and Sensor Fusion algorithms for navigation, localization and collision avoidance enable the ATV to detect and analyze its status. In order to enable a multi-sensor-/multi-system-communication, a module based software platform called Unified Sensor Data Interface (USDI) is currently being developed for the purpose of this project. By using existing standard communication protocols like the Transmission Control Protocol / Internet Protocol (TCP/IP) and the User Datagram Protocol (UDP) for the USDI full compatibility to existing systems is ensured. It allows to access all sensory devices of a system through TCP/UDP-sockets disregarding their physical interface and location (see Fig. 8). Each platform independent module describes a particular sensor of the system and provides a unified data stream (defined in the Unified Sensor Data Protocol or USDP), which can be queried by any evaluating system via network. Additional information about the sensor data (e.g. type, dimension, quantity, data length) and the sensor itself is also provided. Virtual and simulative sensors as well as variable hardware information can also be streamed. A client can open exclusive or accessible-for-all channels. This system allows for heterogeneous Sensor Fusion for navigation and safety purposes in real time.

Within the MSM, readings from three kinds of sensors are fused: A safety laser rangefinder which also maintains safety functions like collision avoidance, ranging information of a wireless sensor network that is based on the IEEE 802.15.4 standard and the odometry of the differential drive motors. The Round-trip Time-of-Flight ranging is based on a WSN.
which can work as a Real-Time Location System (RTLS) [18]. A mobile tag in this RTLS localizes itself by measuring the distances to a set of anchors used as reference points. The anchors are located at predefined positions within a global Cartesian coordinate system. The tag position can be calculated afterwards by trilateration. At least three anchors are needed for an unambiguous localization. The accuracy of the Round-trip Time-of-Flight ranging has been improved by applying an Extended Kalman Filter (EKF) on the range measurement data within the MSM system. The implementation is described in Rohrig et al. [19].

1) Localization: The On-Rail localization of the vehicle is done by using dead-reckoning and light barriers for the slot detection in the multifunctional rail. When driving off the rail, localization is more complex. In order to reach a localization accuracy of up to several millimeters in this case, information of different sensor types has to be merged. Therefore, the localization algorithm is implemented as a Monte-Carlo Particle Filter (MPF) based on Bayesian models using dead-reckoning for the prediction phase, laser rangefinder readings and RF ranging for the update phase (cf. Fig. 9), following the approach described in Thrun et al. [15]. This algorithm is applicable to both local and global localization problems. Furthermore, the modular architecture of the localization algorithm makes it easy to replace the existent sensors (e.g. replacing the laser rangefinder by a 3D-Camera) for future applications.

2) Energy Efficiency Concept: A further key enabler for a successful swarm vehicle realization is an adaptive energy concept on behalf of different requirements. The vehicles operate with batteries as main energy source and they are recharged in the rack system through a conductor rail. Obviously every ATV is lightweight designed and is equipped with an energy-saving IPC and other energy-saving components such as power electronics for the three brushless DC drives used for the traction drive and the lifting device. Additionally, brake energy can be transferred into the energy supply system with slight losses through the brake energy recovering system. Moreover, an adaptive energy concept is implemented in the ATV - any energy supply like LiIon-, LiPoly-, Lead-Acid-batteries, Electric Double Layer Capacitors etc. can be integrated into the system. Prediction of energy consumption for every single path as well as sophisticated energy management are main aspects of the closed loop energy observer system research. The investigation of the energy supply mainly focuses on concepts such as energy recovering systems, energy-efficient path planning and optimized drive control [20]. Eventually a complete system of energy-saving components, intelligent path planning and newest battery technologies guarantee an optimal energy concept for battery-operated vehicles.

IV. CONCLUSION AND OUTLOOK

At present the required invest for an enlargement of a material handling system based on the concept of a Cellular Transport System is proportional to the throughput without any additional costs for adapting (cf. Fig. 10) by meeting the same costs. Effectively, it means that the maximum actual throughput is oriented on the actual required throughput. Through its flexibility, Cellular Transport Systems have economical benefits compared to conventional conveyor systems, which have to be designed oversized to meet future requirements or to retain singular transportation peaks.

As an example, a conventional warehouse and a pick-up zone with an output of 50,000 order lines/day, max. 2,000 transport units/h in the pick-up zone and an average source-
sink distance of 50 m is taken for the rough calculation. The layout is given by the following illustration:

![Fig. 11. Conventional Conveyor System](image1)

Compared to the previously described warehouse conveyors in the pick-up zone are replaced by the vehicles, only picking stations are a static part of the pick-up zone (Multishuttle Move realization):

![Fig. 12. Cellular Transport System](image2)

To calculate the same output power (2,000 transport units/h) with the MSM system the following assumption is made: with the average velocity of 1 m/s, a docking velocity of 0.3 m/s, an average distance of 22 m and 2·4 s picking time, a single Multishuttle Move achieves a retrieval power of 105 transports/h. So 19 MSMs are required for double cycles (simultaneous loading and unloading) or 38 MSMs for single cycles (only loading or unloading) to reach the output power of 2,000 transport units/h. The vehicle reserve is approximately estimated at 25% for recharging, transports in rack and traffic loop ways. Because of the comparable costs for both systems, the Cellular Transport System has the advantage over the conventional system, at least with regard to flexibility and changeability. A further part of research is the comparison between the autonomy of an individual in the swarm and the Swarm Intelligence of the compound. The natural aspect, that an individual is not able to solve complex tasks can not be applied to technical realizations. For example, simple transportation tasks have to be solved by an individual vehicle without any support from other vehicles - this is a contradiction to the Swarm Intelligence. So economical (how much costs autonomy?) and functional (how much autonomy is needed?) aspects set up the limits for the swarm and the autonomy level. These aspects are in the major focus of the future research activities.

**REFERENCES**


