Development of a Holonic Free-Roaming AGV System for Part Manufacturing

Olivier Roulet-Dubonnet[1], Morten Lind[1], Lars Tore Gellein[3], Per Åge Nyen[3], Terje Lien[1], and Amund Skavhaug[2]

[1] Department of Production and Quality Engineering, The Norwegian University of Science and Technology

[2] Department of Engineering Cybernetics, The Norwegian University of Science and Technology

[3] Department of Production Engineering, SINTEF Technology and Society

Abstract. This paper presents an Automated Guided Vehicle (AGV) system under development and its industrial background as a support system for an automated paint department. The focus is on demonstrating how the holonic architecture can be used to implement a flexible AGV system. The system is composed of autonomous AGV holons who cooperate, directly or as groups, with other holons such as robot holons, vision-system holons and order holons to produce the real parts. The holonic architecture is described in detail and example use-cases presented.

1 Introduction

A niche for small and medium enterprises is to produce individually tailored products or services. If the production is done on a large scale, this is called mass customization[1,2] and requires highly flexible automated production systems. The new generation of free-roaming Automated Guided Vehicles (AGV) can play an important role in this pursuit for flexible automation. AGVs are ground robots, usually used for transportation purposes on the manufacturing shop-floor. Taking fully advantage of the free-roaming AGVs require an integration into the manufacturing systems and a flexibility that the hierarchic, sequential systems currently implemented on most shop-floors do not offer.

Holonic manufacturing[3] is a promising architecture for the development of the new kind of flexible manufacturing systems needed. Holonic manufacturing is a highly distributed control paradigm that promises to handle frequent changes and disturbances successfully[4]. It combines features of both heterarchic and hierarchic organizational structures and is based on the concept of autonomous cooperating agents, called 'holons'. Holonic manufacturing is related to multi-agent systems (MAS), a paradigm derived from the distributed artificial intelligence field, but has some key differences[5]:

– Holonic manufacturing is a concept while MAS is a concept and a technology. It is possible to implement holonic manufacturing using MAS technology.

V. Mařík, T. Strasser, and A. Zoitl (Eds.): HoloMAS 2009, LNAI 5696, pp. 215–224, 2009.

– A holon can represent simultaneously a whole and a part of the whole: a holon can be composed of several lower level holons.
– Some holons per definition represent and contain physical devices while agents are normally software components.

AGV systems are, by nature, distributed and, as such, we see the holonic paradigm as a good candidate for the architecture of AGV systems. By AGV system we mean one or more physical AGVs and the control and communication software that enable them to receive orders, schedule and execute them.

A systematic review of published papers on material handling in manufacturing systems was performed, with a focus on holonic systems. There are many publications on holonic manufacturing systems but only a few concentrate on material handling. In one of the first papers on the subject, Liu[6] proposes a distributed holonic architecture with one staff holon, where all service requests are sent to and handled by the AGVs themselves. Srivastava[7] presents an approach for conflict-free shortest path, minimum time motion planning and deadlock avoidance for AGV systems. It also presents an architecture for AGV systems which is influenced by its focus on zone algorithms. The architecture is partially reused in our research project. Babiceanu, in his PhD thesis[8], proposes a holonic-based control system for automated material handling systems. His thesis focuses on scheduling and he shows that the results, obtained by running the holonic algorithms, are close to the optimal solution. Most publications on transport systems focus on AGVs running on fast tracks with fixed crossing nodes and empty pathways[6,7,9]. They do not investigate the case of free-roaming AGVs driving in a stochastic environment together with other vehicles, manufacturing artefacts and humans.

This paper presents an Automated Guided Vehicle (AGV) system under development and its industrial background. The focus is on demonstrating how the holonic architecture can be used to implement a flexible AGV system. The system is composed of autonomous AGV holons who cooperate, directly or as groups, with other holons such as robot holons, visions-system holons and order holons to produce the real parts. The holonic architecture is described and example use-cases presented.

The remainder of this paper is organized as follow: Section 2.1 presents the industrial test case for the AGV system. Section 3 describes the holonic architecture of the system. Section 4 considers some use-cases showing how the holonic architecture can support the required flexibility. Finally, section 5 presents discussion and conclusion.

2 Industrial Application and Physical Devices

2.1 Industrial Background of the AGV System

The industrial background of the AGV system is two medium sized enterprises producing consumer goods. Their manufacturing process is a typical example of mass customization: they manufacture individually tailored products on a large scale.

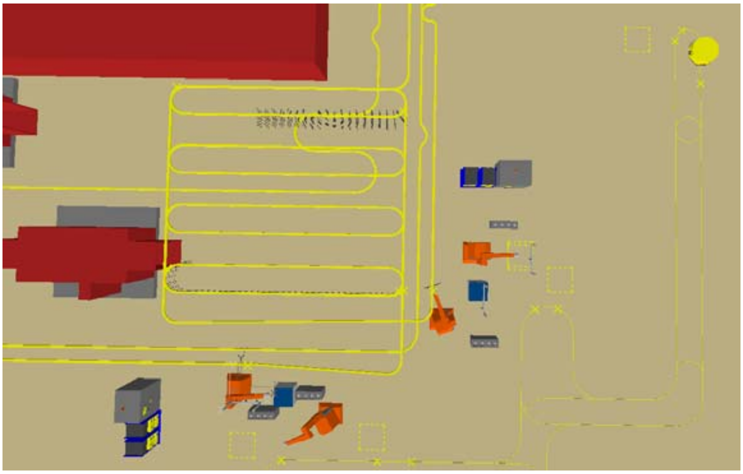

Fig. 1. The uploading(right side) and downloading(bottom side) cells of the paint department in QUEST

This paper is written as part of a larger project which focuses on the automation of the paint department and its surrounding logistic processes. In an earlier work the current paint process was analyzed and a new automated paint solution was proposed. The new automated paint-shop department and its logical control has been thoroughly documented. The result of this work serves as a reference system to be used for the further development of the proposed holonic AGV system.

Figure 1 shows the proposed system simulated in QUEST, a commercial simulation program. The heavy yellow wires are the tracks of the overhead conveyor which transports the painting carriers past the upload cell, the download cell, and through the paint process. All the red boxes make up the devices for the paint process, such as washing, drying, painting, hardening. The four robots are grouped in an upload cell and a download cell. In the upload cell one robot grips parts from bin and places them on an AGV, the other grips part from the AGV and hangs them on the conveyor belt. The download cell has not been setup yet but follows the same principles.

The role of the AGV system in the paint process is to perform the resupply of components for upload, and the transfer of downloaded components. The AGV system will also perform the transport tasks inside the cells, in-between the industrial robots, thus allowing for a better utilization of the shop-floor area e.g. by physically splitting the bin-picking operation from the uploading operation. For the industrial partners the AGV system is not viewed as a separate goal but rather as a support service for the manufacturing cells we are working on and eventually the rest of the manufacturing process.

A concrete challenge in this transport application is that it will not be possible to reserve pathways in all areas where the AGVs will be driving: There are no static paths nor static nodes and the pathways cannot be guaranteed to be free of obstacles. This uncontrollable environment requires advanced obstacle avoidance capabilities. This fact, as well as the importance of flexibility in this project, has driven our focus on free-roaming AGVs.

2.2 The Laboratory Demonstrator

To demonstrate the feasibility of the proposed paint process, and to experiment with new technologies, a laboratory demonstrator was setup. The functionality contained within the upload cell together with the corresponding resupply of components constitutes the basis for the laboratory demonstrator.

The implemented AGV part of the laboratory demonstrator consists of a working AGV that communicates with a vision system used for accurate positioning within the laboratory. The system is in the process of being extended: two AGVs are being assembled and several more are planned. In addition, several vision systems are being set up. By design, the AGV fleet will be heterogeneous to be able to experiment with AGV-dependent optimization for the manufacturing system.

The first test case is to transport components within the uploading cell. A bin-picker robot picks parts from a container and organise them on an AGV. When the task is accomplished the AGV drives to an upload robot where components are uploaded to the power-and-free conveyor to get painted (cf. Fig.2).

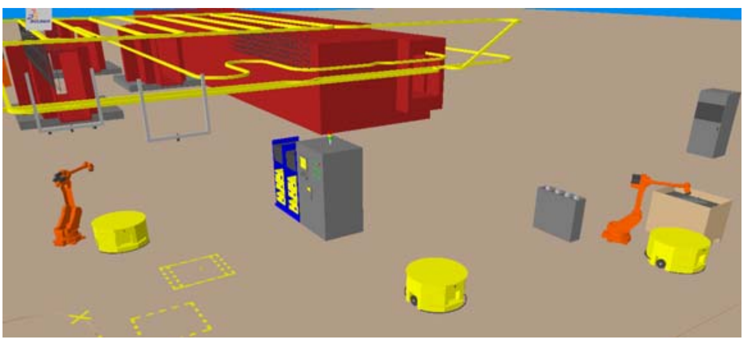

Fig. 2. The split upload cell using AGVs for transport between the two robots

3 The Holonic AGV System for Part Manufacturing

AGV systems are, by nature, distributed and flexible. When they, in addition, are composed of free-roaming AGVs, with local navigation ability, they match physically the definition of autonomous holons in the holonic manufacturing concept. As such we see holonic manufacturing as a natural choice for the control architecture of AGV systems.

Compared to a more traditional architecture the holonic architecture offers off-line and on-line flexibility that makes it possible to implement the required adaptability of the system, thus exploiting the possibilities offered by free roaming AGVs. The off-line structural flexibility of the holonic architecture enables the implementation of features of heterarchic and hierarchic organization[4]. In addition, holonic manufacturing has a built-in concept of on-line aggregation of holons into a new holon, that can be used to represent the physical, temporary association of holons to a specific task (cf. Sec.4).

The AGV system has been designed based on the published literature on holonic manufacturing and material handling system. The system is an implementation of the PROSA architecture[4] and is in several aspects inspired by the work done by S.C. Srivastavaet al[7] and Babiceanu et al[10].

Scalability in holonic material handling systems is a central issue which has been little mentioned in publications. In the design process of our proposed AGV system we have taken scalability issues into account from the beginning. We have used a distributed architecture and have avoided communication bottlenecks and central servers where practical.

3.1 The Holons

The proposed AGV system is composed of the four base holons defined in the PROSA architecture.

- Resource holons represent the physical devices. In our cases resource holons are AGVs or groups of AGVs.
- Product holons represent the part to manufacture. In our case they are containers for information about the parts to transport.
- Order holons are generated for each transport request. They are the driving force of the holonic system. They compete or collaborate with each other to allocate AGVs and process their transport need.
- Staff holons are adviser holons. They do not execute actions directly but give advices to other holons. A typical example is the scheduling holon which generates an 'optimal' schedule and advice it to other holons.

A simplified overview of the architecture is shown in Fig.3. Resource holons are represented in rectangles, order holons in ovals and staff holons in hexagons. It shows independent AGV holons and AGV holons aggregated in an AGV-group. It also shows one path-planning holon inside an AGV holon, although this is not a requirement: path-planning holons can be part of AGV holons or shared.

The main components of the AGV system have been split into autonomous entities: low-level AGV control, traffic, scheduling, path-planning, ordering, localisation. Not all components need to be implemented as holons. Entities can be implemented as separate processes, on servers or AGVs, but as soon as they can deliver useful information to other entities it makes sense to implement them as holons. Some entities, like ordering, are implemented using many order holons.

It is our experience that industrial partners often desire central algorithms for critical functions like scheduling. A possible implementation of such critical functions is to use a unique central holon or several holons using the same algorithm.

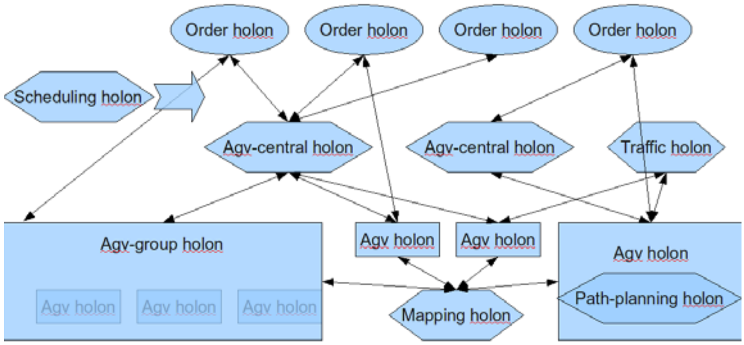

Fig. 3. Simplified overview of the AGV system control architecture

The algorithm must have a deterministic result so that holons eventually will end up with the same conclusions. This requires a system resilience to temporary disagreements. Resilience can be implemented in a holonic system by using staff holons giving advices, and not orders to other holons. In the disagreement period, the obtained result might not be optimal, but we think that the added flexibility and scalability of the solution overweight this issue.

A more detailed description of the main holon types is presented in the following subsections.

The AGV Holon. The AGV holon is the resource holon controlling the physical AGV and as such it runs directly on the physical AGV. In our system the AGVs are required to be able to run holons and communicate through a wireless network.

An AGV holon has a queue of order holon tasks which are periodically rescheduled. To support AGV-groups and special situations within the manufacturing cell AGV holons can enter a slave-state, thus letting another AGV holon or holon from the manufacturing take over the high level physical control of the AGV.

The Order Holon. The order holon is the specialized order holon for the AGV system. An order holon is created by a generic manufacturing order holon to solve a transport issue.

Order holons are the driving force of the holonic system. As long as its transport request is not executing, an order holon constantly queries the AGV-central holons for available AGVs and expected scheduling data. If it gets a better offer, or does not yet have an AGV assigned, it contacts the candidate AGV holon and request to be appended to its order queue.

The order holon also periodically contacts its assigned AGV to keep each-other aware of their current state. If an AGV holon does not get information from a order holon for a period of time, it removes it from its transport queue.

The AGV Central Holon. The AGV-central holon is a staff holon. Its name is inspired by an analogy to a ’taxi central’. The role of the AGV-central holons is to increase scalability by providing an interface to AGV holons. Each AGV uses one AGV-central holon chosen using, for example, geographic parameters.

AGV-central holons answer queries from order holons and advice them to an AGV. Order holons call several AGV-central holons and choose the best offer.

The Group Holon. Group holons are created when several AGVs link themselves together to a special task. The group holon is an abstract holon type inherited by specialized group holons cf. Sect.4.1. In some cases it may appear as one AGV holon to other holons.

The Scheduling Holon. The scheduling holon is a staff holon providing scheduling data to other holons. These holons are a necessary complement to local scheduling information from the AGV holon, since AGV holons have a limited vision of the global manufacturing system. The scheduling holons give advices to order holons or AGV-central holon to influence the choice of AGVs by order holons.

By communicating with other holons it keeps an up-to-date view of the manufacturing system, generates an 'optimal' scheduling and tries to get it applied by trying to re-affect order holons to AGVs.

The Path Planning Holon. The path-planning holon is a staff holon. It is a holon computing an optimal transport path for an AGV. It needs a map of the shop-floor obtained through the mapping holon and optional information from the online-traffic-control holon. Since the AGVs are capable of local navigation, a path is, in our context, defined as a list of points to be loosely reached. The path-planning holon can either be part of an AGV holon or be shared between several AGV holons.

The Mapping Holon. This is a staff holon that collects mapping information from all running AGVs in a geographic area. Mapping is a crucial feature of AGV systems for localization, navigation and path planning. Some of the AGVs are using Self Localization And Mapping algorithms, thus they depend on an up-to-date map to know their current position.

The idea is that all the AGVs participate in the on-line mapping of the shop-floor, thus reducing the need for manual updating of the current map. AGVs send periodically a report on their modification to their internal map, thus informing other AGVs of obstacles and changes on the shop-floor.

This system can used as the basis for the implementation of specialized scout AGVs that constantly investigate the shop-floor and maintain an up-to-date map. Unused AGVs could also be used to investigate unknown areas.

The Online Traffic Controller Holon. This is a staff holon whose role is to survey the AGV traffic in a geographical area and give advices to AGV holons to sort out conflicts and avoid congestions.

4 Holonic Use-Cases

This section details some use-cases as they have been defined for the AGV system. They focus on showing how the holonic architecture can be used to increase the flexibility of the AGV system.

4.1 AGV Holons as One AGV Holon

By this cryptic name we mean applying the holonic fractal concept to link together several AGVs to a special task. A group AGV can appear to the external holonic environment as a specialized AGV holon. The constituting AGV holons do not reply to requests as individuals but through the group holon. Examples of such applications are:

– Replace a palette conveyor with several AGVs: Several AGV holons enter a special 'pallet' state and one AGV holon start acting as a pallet conveyor supervisor. Required specialized holons are started. e.g. scheduling.
– Create a transport chain for an transport order with high priority.
– Transport large objects. The AGVs can link together their lower-level controllers thus allowing on AGV holon to control directly all physical AGVs. The AGVs can even be linked together mechanically.

4.2 AGV Holon as Part of a Manufacturing Cell Holon

A fundamental concept of our system is that AGVs are an integrated part of the manufacturing system. AGV holons can be assigned to a cell holon or, even, a robot holon for a given time.

– AGVs can be assigned to a robot system, thus allowing direct ordering from the robot to the AGV, effectively bypassing all scheduling and negotiations with other holons. It can be used, for example, to implement efficient cooperation between two robots out of each others reach: when a robot is finished placing parts on the AGV it communicates directly to the AGV to send it to next robot.
– In a similar idea AGVs can be used to increase the reach of an industrial robot. Thus allowing a smaller robot to temporary accomplish tasks usually requiring bigger robots.
– AGVs could also be used to push objects in a cell if required.
– AGVs can be affiliated to a robot on a track. An example taken from our paint conveyor: If instead of using a power-and-free conveyor for the hangers we would use a simple trolley conveyor and an industrial robot on rail. We could then follow the robot with the AGV while it is hanging parts on the conveyor, thus avoiding travel back and forth for the robot to pick parts. This solution would require a precise positioning system for the AGV or/and a vision system to give real-time part positions to the industrial robot.

4.3 The AGV as a Self Contained AGV System

In this concept a physical AGV represents the whole AGV System: the entire AGV system is started by starting one AGV. This feature is desired to simplify the administration of the system and to solve some specific scenarios e.g. transport to external storages areas outside the wireless network.

An AGV holon has a list of holons to connect, e.g. path-planning holon and AGV-central holons. Some of them are optional and others are required. If a required holon is not found then it is started either on the local AGV or on an available server.

A consequence of allowing holons to start other required holons, is that a mechanism is required to handle 'excessive' holons of one type. This is typical issue of distributed systems, holons of an excessive type need a consensus on who will close itself.

5 Discussion and Conclusion

In this paper we have presented the industrial background of an AGV system under development. The need for a flexible solution has been identified and a control architecture using the holonic manufacturing paradigm proposed. The paper has also presented, through several use-cases, how the holonic architecture can support the required flexibility of the AGV system.

In our proposed system there is clearly an emphases on the process viewpoint as defined in the reference PROSA architecture: It has been a conscious choice to focus on the AGV system as a support component of the manufacturing cell. As a consequence, the described use-cases are concerned with the interactions between the AGVs and the manufacturing cell and much less with high level scheduling and traffic management. One might say that AGV system presented only partially defines a material handling solution but we see this system as working subsystem from which a larger system can be composed, an important characteristic of holonic manufacturing systems[11].

6 Future Work

Implementation of the proposed holonic AGV system will continue during the next years in cooperation with the industrial partners. Much work has yet to be done to evaluate the performance, scalability and flexibility of the proposed holonic system and to demonstrate the industrial feasibility of the proposed use-cases.

Acknowledgements

This paper presents research results obtained through work in the IntelliFeed and CRI Norman projects sponsored by The Research Council of Norway.

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