Holonic Manufacturing Paint Shop

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Abstract. In pursuit of flexibility and agility within discrete manufacturing, the surrounding logistics and handling processes of a paint shop is under construction as a laboratory prototype application. Holonic Manufacturing seems to be a promising strategic paradigm and architecture to use for a system characterised by production logistics and control. This paper describes the physical devices to be used; the desired functionality; and the basic logic control designed. Additionally, the ideas for holonification based on the already designed logic control is presented.

1 Introduction

Distributed decisions and coordination of autonomous sections in manufacturing have been around as long as complex manufacturing. By complex manufacturing in our context, we mean dealing with multiple complex products and extensive sharing of manufacturing equipment across different simultaneous product variants, i.e. with frequent changeovers and reconfigurations on the shop floor. In the recent decades there has been focus on the flexible automation of these entities. The enabling technologies for this may be traced back to the birth of numerical control and computational intelligence in the 1950s.

Holonic Manufacturing is a paradigm for pervasive manufacturing automation, ranging from (and integrating with) the lowest level of real time shop floor control and all the way up to company or even corporate level. It covers most aspects of manufacturing, be it machine to machine cooperation or order to production department interaction.

The concept of a *Holonic Manufacturing System* (HMS) date back to the early 1990s when the *Intelligent Manufacturing Systems* (IMS) initiative set out a project with that name. The term *Holon* was coined by Arthur Koestler[1], some 40 years ago, for capturing the dualistic capabilities of autonomy and cooperativeness withing a single entity. The concept was found suitable to encompass the entities, physical as well as abstract, in manufacturing control and management.

There exist some architectures for Holonic Manufacturing Systems, such as PROSA[2] and ADACOR[3]. PROSA is strictly a reference architecture and

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introduces the central concepts of basic holons: order, product, resource, and staff holons. High level scenarios illustrate the interactions of the different holon types. ADACOR is also an architecture, but with a different naming of the holon types. Notably the ADACOR supervisor holon differs from the PROSA staff holon, in that it formally coordinates the dynamics of holon aggregation and subordination. Leitão and Restivo applies the ADACOR architecture to a (partially simulated) machining and assembly workshop in several papers, see e.g. Leitão and Restivo[4,5].

Two standards are highly relevant for Honlonic Manufacturing on very different levels: IEC61499 and FIPA; cf. Mařík et al.[6]. The IEC61499 standard regards a function block structuring of design and code for low level control oriented holons and their interactions. At the higher level, FIPA is a standard for ontology based agent communication.

The laboratory prototype described in this paper is a part of IntelliFeed, a cooperative project between the research institutions of the authors and industrial partners, supported by the Norwegian Research Council. Relevant and related projects also based at our research institutions are RAMP and CREAM; both part of the CRI NORMAN research program[7].

The particular laboratory prototype system we present here has its origin in the recognition that much manual labour is associated with the materials handling around paint shops in manufacturing industry. In itself, the full or partial automation of such systems will have a good potential for reducing trivial manual labour. But the potential is extended further if the automation is flexible and responsive, enabling the paint shop system to integrate with other parts of the entire manufacturing system.

This paper is organised as follows. In Sect. 2 the physical devices and their layout is described. Sect. 3, presents aspects of a holonification of elements and control. Discussion and future challenges is presented in Sect. 4.

2 Application Overview

In this section we describe the laboratory layout and the associated physical devices.

A real paint shop roughly consists of a painting system, a part upload station, a part download station, a painting carrier upload station, a painting carrier download station, and an overhead conveyor system. The painting carriers are hanging from the conveyor trolleys and are transported through all the stations and the painting system.

Our current goal is automation of the processes and materials handling at the part upload station. In the future, the other stations will undergo equivalent automation projects in a successive manner.

2.1 Laboratory Application Overview

A sketch of our initial laboratory system setup, currently used for simulation with QUEST, is shown in Fig. 1. The transport AGVs and a *Parts Arrangement*

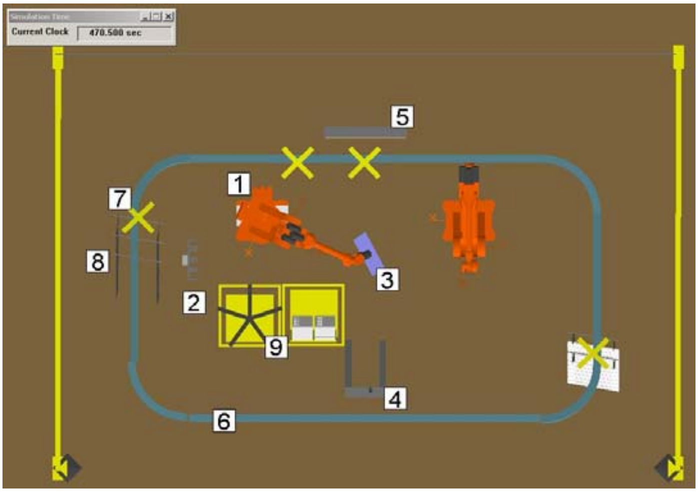


Fig. 1. Overview layout of a planned laboratory system. 1) *Upload Robot*, 2) *Upload Tool Rack*, 3) *Mounted Upload Tool*, 4) *Upload 3D Vision System*, 5) *Backlight Screen*, 6) *PnF Overhead Conveyor Track*, 7) *PnF Switch*, 8) *Painting Carriers*, and 9) *Local Part Storage Carriers*.

Station are not seen. The setup is planned for a Power-and-Free (PnF) overhead conveyor, though the conveyor type has not been decided for yet. As will become clear, a PnF conveyor is definitely to wish for when automating the uploading of parts to the painting carriers.

The robots we have available in the upload area are two Nachi SC15F, which are floor mounted within reach of each others and the conveyor track. Both are equipped with a 6D force sensor at the wrist. One of the Nachi robots have a modified controller, giving a direct $100 - 200\,Hz$ interaction with the servo controller using UDP over Ethernet. The other Nachi controller can easily be modified likewise.

In addition we have an ABB IRB 2400 with an S4C+ controller, also located in the laboratory but well outside the conveyor area. The ABB robot is connected to the rest of the system over an RS232 serial communication link. It has its own standard robot controller programmed in the complex RAPID control language. The program execution is hard real time, but interaction can only be through parameter modifications before real time execution.

2.2 Part and Painting Carrier Handling

The part uploading is performed by a robot which has access to parts from a local part storage. The upload robot picks a part from one of the local storages and then attaches the part onto the presented painting carrier on the conveyor. Given the part and painting carrier type, as well as known painting carrier capacity state, the support system will be able to control the robot to attach the part at some free site on the painting carrier.

The painting carriers may have very different geometries and have a load capacity from one to several tens of parts. Frequently each painting carrier type may match different part types; this has, of course, a high impact on the sequencing of part batches. Some painting carrier types are adjustable and can host a whole family of parts types. The automatic handling of painting carriers is not a part of the initial laboratory system. Manual change of painting carriers will be performed, when need be.

The process of localising the attachment points on some of the simpler painting carriers, with the Scorpion 3D vision system from Tordivel, has already been implemented and verified. For stable identification and analysis of all painting carrier types, it may be necessary with more vision system or other sensory systems.

To ensure mechanical stability of the painting carrier under identification, analysis, and upload, a controlled clamping mechanism will be implemented underneath the PnF switch at the upload station.

2.3 Conveyor System

The conveyor system has not been decided yet. This decision is of cardinal importance for a lot of other hardware decisions, as well as the control logic.

We concentrate our efforts around the PnF conveyor, simply because of the severe implications which would arise by using the more common *Chained Trolley* conveyor[8]. The main difficulty with a chained trolley conveyor is that all trolleys travel at constant speed at all times. Thus either the parts must be uploaded onto the painting carriers in motion, or the painting carriers must be sidetracked to a small PnF conveyor loop with a buffer for reattachment to the main conveyor.

2.4 Painting Process Scheduling

For a given paint process setup, with parameters for rate of paint added and geometric configuration of parts, it is desirable to use the maximum speed of the conveyor while still meeting the paint quality requirements. Or, for given speed of the conveyor and geometric configuration of parts on the carriers, it is desirable to minimise the rate of paint added, while meeting the required paint quality, thus minimising the amount of wasted paint.

Upload and download capacity and equipment utilisation makes up a delicate trade-off. This depends on the pertinent part type, painting carrier type and painting process parameters. In a simple batch controlled system, where only one part type and one painting carrier type is on-line at any time, there will often be under-utilisation in one or more of the upload station, the download station, and the painting system.

If mixing of parts within each painting carrier, or in the sequence of painting carriers, is allowed for, more freedom is given to the optimisation and the problems of under-utilisation can be remedied somewhat. The implication is a much more complicated logistics around uploading and downloading.

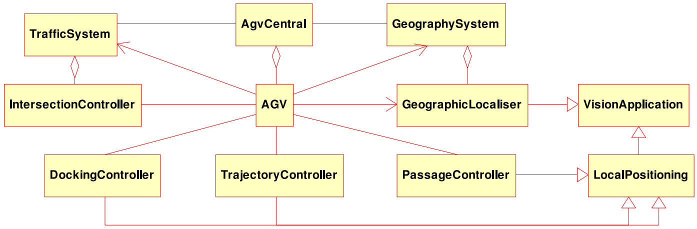


Fig. 2. A class diagram showing some important aspects and subsystems related to the AGV system

2.5 AGV System

Figure 2 shows a class diagram illustrating some important aspects of a multi-AGV system for material transport. Multiple AGVs are being built at our laboratory and the software system is in the design phase. The physical AGVs and AGV control system is based on earlier experience with a prototype AGV and vision based positioning system.

The conceptual AGVs, being hosted entirely on the physical AGVs, are central components in the AGV system. We initially assume that all of the AGV localisation functionality will be based on vision applications. This is based on earlier successes with developing a vision based AGV localisation system.

The traffic system gathers information from and supplies information to the client AGVs about viable paths in the whole of the roaming area. It will be the the coordinator for pre-reservation of long term trajectories of the AGVs, whereas the AGVs themselves can react to short term (emergency) trajectory interferences. Specialised intersection controllers at known congested areas are regulatory rather than guiding in their relation with the approaching AGVs.

The geography system is the general global localisation system for the AGVs. It is demanded that the cameras of the geographic localiser servers cover the entire area where the AGVs may roam, and can serve the client AGVs with real time location information.

Specialised conceptual controllers for local positioning and control may be defined to serve purposes relevant to situations or tasks, partly external to the AGV system. Examples, relevant to our laboratory system are docking, trajectory, and passage controllers.

3 Holonification

Based on the initial plans, layouts, and experiments with uploading of parts, a logic control of a paint shop has been designed. The given design is more or less a traditional hierarchical control design.

In this section we sketch our ideas for holonification of the logic control system and the physical devices and layout in the previous sections. Ideally the designed explicit logic control will emerge out of the holonic control system currently under development.

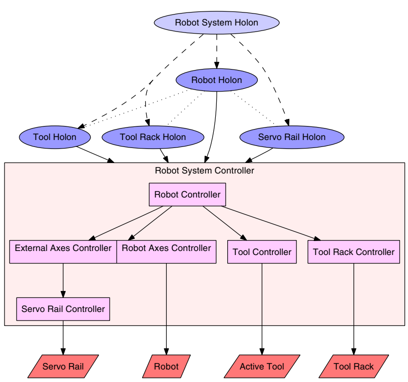
We are not suggesting that we have a complete design for the holonic system, but this is a description of our initial thoughts and ideas on how a holonic architecture will be applied in the control and management system.

3.1 Resource Holons

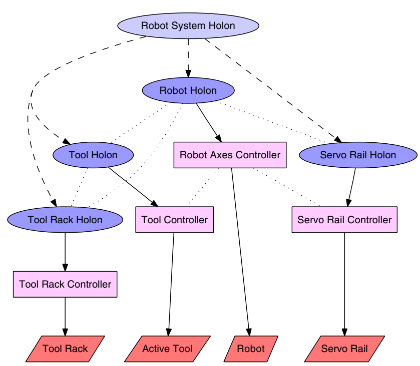
The resources, holons associated with physical devices, are related to the set of devices discussed in Sect. 2. This need not be a direct mapping, and indeed the devices described in Sect. 2 give too little detail to identify the entire set of resource holons.

The Robots. plays a central role to the part handling processes. They are the devices with the hardest real time aspects which we try to holonify. Normally the real time aspects of the motion control is integrated with other real time tasks inside the commercial controller, and closed to the intervention in a broader system, cf. Fig. 3(a). This should not be so in a deeply holonified system, since it enables only a virtual high granularity of the holonified control; this is illustrated in Fig. 3(a), by the low level holons all addressing the integrated robot controller for accessing their logical control functionalities. The device controllers' functionalities are hierarchically organised inside the commercial controller.

What is usually meant when referring to *a robot* in a manufacturing work station is the physical arm, the robot controller, and a whole range of various peripheral devices and their controllers, i.e. the whole *robot system*. These peripherals may consist of tools available for the robot, external (rail or gantry) axes for the robot, and even the whole range of sensors external to the robot arm. This is often well justified due to the *black hole* nature of commercial robot controller, in which coordination with external devices is possible only if these devices are integrated into, and controlled by the robot controller. The real time



(a) Centralised robot control system in vendor controller.



(b) Distributed holonic robot control system.

Fig. 3. Traditional integrated and holonic robot systems in automation. Holons are shown in blue colours and controllers and physical devices are shown in red colours.

aspects of the entities integrated into the commercial controllers is a good reason for the tight integration, but is an example of both types of *lock-in* processes described by Mařík et al. [6].

We have made an effort in separating the motion control of the mechanical arm from the control of the peripheral devices. This will enable us to perceive the real robot, i.e. without tools, external axes, etc., as a holonic device, giving a higher true holonic granularity in the holonic system. This is illustrated in Fig. 3(b) where the holons access their physical controllers directly, and where the device controllers are allowed peer-to-peer interaction for hard real time performance.

The robots locations, motion capabilities, and work space envelopes are of high importance to the order and product holons. Even for a homogeneous set of robots with the same product capabilities, a slight difference in location relative to the process location, may give a major impact in process performance. This will be even more expressed in a system of heterogeneous robots. These relations may not be a disadvantage, but rather an advantage, especially if the batch layouts and the scheduler functionalities allow for mixing on-line part and painting carrier types.

We are planning to have two different robot systems in the initial laboratory system. One is the system around the central upload robot and another system around the less described arrangement robot. The arrangement station is where bin picking is taking place, picking single parts out of gross storage carriers and placing them structured to order on local storage carriers, possibly directly on top of AGVs.

The Parts Arrangement Station is the location where parts are taken from gross storage containers and transformed into a pickable arrangement in a local storage carrier. The whole station, once robotised with bin picking capabilities, will be in itself a complex holonic system, if the supplier of the bin picking software and hardware allows it. It will definitely be so, in case we endeavour to implement it in-house.

For the initial phases, however, we must envision the absence of robotisation of this station, thus leaving the bin picking a manual operation. This is by no means in contradiction with the holonic manufacturing thought. On the contrary, one of the forces of the HMS paradigm is that an operator need not be treated or represented differently from any other resource or staff holon. The physical interaction with an operator is slightly different, though the capabilities should not be inferior to that of a robotised processing entity.

The direct interaction of this station with the paint shop system is to the orders and schedulers. Product holons for parts play a role in identifying methods for parts, and possible handling process information. Product holons for the transport carriers play another role of specifying the arrangement of parts into the carrier and possibly some process information for installation of the parts.

The Robot Tools are mountable on the robot arm and customised to handle specific parts. The entire set of tools available to one or more robots, or other handling device, must cover the whole range of parts to be handled by the robots.

In case of multiple tools, they must be organised in a tool rack, to be on-line changeable by the robot system. There will be a tool holon for each tool, but typically only the ones mounted on a robot at any given time will be active.

Fixtures, be it active or passive, may be considered as tools as well, and need not be at a fixed or active location all the time. In that sense, they are no different from what we normally refer to as tools; tools just just differ by being mountable on a robot end effector.

The tool set available to a robot system is of high importance to the product and order holons. A given order holon needs to be able to request from the robot system that it use a certain tool or tool capability, namely one that is compatible with one of the process alternatives in the pertinent product holon.

The Vision Systems planned for the initial laboratory system are comprised by the following four quite different types:

Painting Carrier Vision System: This is the 3D vision system already implemented with Scorpion 3D from Tordivel. It analyses for the points and directions of interest for a empty painting carrier presented to its cameras. This information is used by the upload robot system.

Part Localiser Vision System: Localises the parts for picking positions and orientations in the transport carriers (possibly the AGVs) in the local part storage area at the upload robot system. It is not to be considered a bin picking system, since the parts are at least semi-structured in the transport carriers.

Passage Vision System: The vision system used to guide the AGVs to cross intersection(s) of the transport route(s) with the overhead conveyor system. It is quite simply a matter of determining, in advance, when there will be passage where, and for how long.

Bin Picking Vision System: Used for identifying parts lying unstructured in gross storage carriers or containers.

This list of vision systems disregards the various dedicated and specialised AGV location vision systems, which are considered private to the AGV system.

The integration of the vision systems into holonic vision applications is a matter of letting orders interact with them in various ways, such as reserving for usage, configuring for detailed applications, and querying for or subscribing to information. But most vision system usage is expected to take place on a lower holonic level, integrated in a more numerical and detailed way with the direct consumers of the information, such as robot systems and AGVs.

The Conveyor System. As mentioned earlier, we are not yet sure what type of overhead conveyor system we will install, hence we know little about the controller capabilities and properties. The overall conveyor controller interaction will, however, be controlled by a holon.

In case of a PnF conveyor it will be relevant to find out if the PnF stations can be directly controlled, and thus be integrated with a physical device holon. Otherwise a logical device holon must be set up to access the main conveyor controller. If tracking of the trolleys is possible, it may be relevant to model each trolley as a resource holon. However passive, such trolley holons will at least be responsive to queries regarding arrival time, as well as associated painting carrier and order.

The AGV System. The holonic AGV system is under development, but is developed as a generic AGV system rather than a custom made system for the laboratory paint shop.

It may well be the case that the AGV system exposes its *products*, i.e. the transport and part carrier capabilities and capacities. This is a necessary information to access for the orders and schedulers in the paint shop system. There may be various alternative procedures for creating transport and configuration orders in the AGV system from the paint shop system. One is to send transportation requests to one or more AGV centrals, receiving an offer after negotiations internal to the AGV system. Another, lower level alternative is to directly create a transport order in the paint shop system and then have the pertinent paint shop order holon interact with relevant individual AGVs and AGV system schedulers, to settle a suitable contract. Both alternatives should be offered, since they may have their strengths and weaknesses in different situations.

3.2 Order Holons

The orders in the system contain the static data relevant for the associated order holons. We think of the orders as a hierarchy where the highest level is a production plan, being a quite simple list of parts for production during the day. Typically, in manufacturing systems today, the production plan for the day has been determined over night, or some days in advance, by the company ERP system. In a batch oriented system such as a paint shop, the sequencing and scheduling of the production plan is done heuristically by the operators at the paint shop. All parts produced in the painting systems we know of, are produced for intermediate storage, so the parts produced are used no earlier than the following day.

An illustration of a possible division of orders for our laboratory case is shown in Fig. 4.

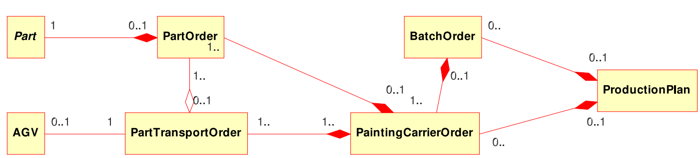


Fig. 4. Overview of aggregations and compositions among the order holon classes

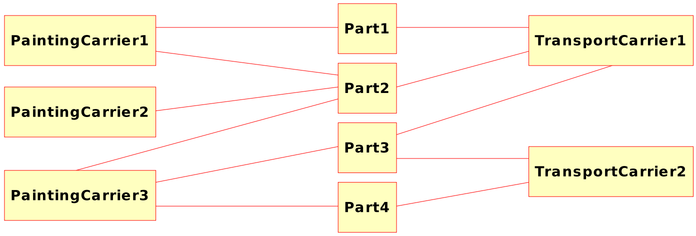


Fig. 5. Illustration of a match between painting and transport carrier types and part types in a simple example with four part types and three carrier types

3.3 Product Holons

The product holons for the upload station must contain a specification of how to attach a compatible set of parts onto a given painting carrier type. If similarity of parts and optimality of the painting process allow for it, certain painting carrier types will be able to host a range of part types. This matching is exemplified in Fig. 5.

The identical problem of matching of carriers and parts arises for transportation purposes. Shown also in Fig. 5 is an example of a transport carrier type to part type match.

In the cases described, the product holons are very static and persistent structures. This will be the case with predefined mixing of part types on the same carrier type. But to be truly flexible, the mixing should be possible to decide for in an on-line manner, i.e. some scheduling functionality may have an on-line or real time interaction with the uploader system. In this case some volatile product holons will be configured ad hoc for a single painting or transport carrier, or configured for the sake of some number of carriers; e.g. for mixing and completing a set of batches.

3.4 Staff Holons

Of staff holons we most certainly will have schedulers. In fact, one of the first overall control mechanisms we should experiment with, may be to emulate the decision system of the responsible operator in the real paint shops. The responsible paint shop operator has a fundamental input the painting day plan from the company ERP system. He makes on-line scheduling decisions based on a variety of parameters and feelings, which we should make an effort in investigating.

In addition to the vaguely interacting staff holons from PROSA[2] we embrace the more directly interacting supervisor holons from ADACOR[5]. We believe both aspects are good to have in separate entity types, whereas Leitão and Restivo[5] seems to suggest that the supervisor holon is more than a staff holon, and replaces it. The staff holons hold the responsibility for planning, long term scheduling, and global optimisation. And the supervisor holon, under normal system operation conditions, should have responsibility for and control of more local aspects of short term scheduling, optimisation, holon structures, and orchestration.

The distinguishing difference between staff and supervisor holons, in our interpretation, is that staff holons are available as a service and help to other holons, whereas decisions by supervisor holons have to be respected by other holons. Thus staff holons can be thought of as finding solutions to problems and supervisor holons to be executors and enforcers of such solutions. As per design of the supervisor holons by Leitão and Restivo[5], they lose their powers when disturbances arise, regaining them again when it is possible to restore local order. These views are not in contradiction with the PROSA and the ADACOR architectures.

4 Discussion and Future Work

While we will proceed with implementing the holonic control and management system in the near future, further development and implementation of hardware and device specific control software will take place in parallel.

One might say that we are still only in the analysis phase of developing the holonic manufacturing system for our laboratory prototype. We feel well into that phase, and have begun considering high level design issues. One pressing issue that we currently have much emphasis on is choosing middleware and platform.

Inspired by such works as Shin et al.[9], one viable path to follow is to start without a platform and use CORBA as middleware. This will enable us to progress fast by implementing our own platform using the Python Programming Language. Python is a language and platform with which we have good experience regarding both the management and soft real time domains of software. The direct implementation of the holons based on CORBA references invocations does not really support a fully flexible holonic platform. However, the platform we develop can be revised into a FIPA compliant one, adding complex communication abilities where and when it is needed.

Another path to follow might be more traditional, like the applications of ADACOR[5], where Leitão and Restivo use the FIPA compliant, Java based JADE agent platform. In order to apply our experience with Python we would use the FIPA compliant, Python based SPADE[10].

5 Concluding Remarks

At the current state of design of the laboratory paint shop prototype, we have gained such confidence in the HMS paradigm, that it will be used for the prototype, and recommended to the industrial partners in the project. The HMS paradigm has turned out to be a major initiator in bringing our minds from the offices towards the laboratory.

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