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Distributed, autonomous control in production of jet turbine parts

Per Aage Nyen^a, Espen Polanscak^b, Olivier Roulet-Dubonnet^a, Morten Lind^a *^a SINTEF Raufoss Manufacturing AS, Enggata 40, NO-2830 Raufoss, Norway^b GKN Aerospace Norway AS, Kirkegårdsveien 45, NO-3616 Kongsberg, Norway* Corresponding author. Tel.: +47 73 59 30 86. E-mail address: per.a.nyen@sintef.no

Abstract

An industrial prototype of a distributed, autonomous shop floor control system (HolMS) has been developed based on the PROSA reference architecture for holonic manufacturing systems. The HolMS system challenges the concept of visual control as prescribed by the Kanban mechanism in the Toyota Production System. Instead, it applies a market oriented service request/service offer bidding mechanism. A basic premise for obtaining this on the shop floor is that the different processing units are able to communicate. This has been accomplished by developing OPC UA wrappers for all the CNCs, robot cells and tracking devices involved. The HolMS prototype has been demonstrated at the jet turbine vane department of GKN Aerospace Norway.

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1. Holonic manufacturing

This paper presents the development process of a shop floor control system prototype based on Holonic Manufacturing fundamentals. This includes the lessons learned throughout the process and the potential improvements to be investigated and implemented in the next steps. The motivation for the paper is to bring forward some issues in the process of industrializing research based results from concept level to an operational prototype.

The concept of *holons* was originally presented by the Hungarian writer Arthur Koestler in his book *The Ghost in the Machine* from 1967 [1]. In this book Koestler attempts to fill in the gap 'between the atomic approach of the Behaviourist and the holistic approach of the Gestalt psychologist' [1] in contemporary social psychology by introducing the word *holon* to describe the dual nature of sub-wholes and parts in social organizations and living organisms. He describes the holon by its basic polarity: 'The self-assertive tendency is the dynamic expression of the holon's wholeness, the integrative tendency, the dynamic expression of its partness' [1].

In the 1990-ies the Intelligent Manufacturing Systems

(IMS) programme launched a project for developing the holonic manufacturing paradigm with the characteristics of system components of autonomous modules and distributed control. The basic idea was to 'translate' the system concepts of Koestler into the world of industrial manufacturing by combining the best elements from both hierarchical and heterarchical organization. The project presented three very basic definitions each contributing to the inner heart of holonic manufacturing: the *holarchy*. The three definitions were presented as follows:

Holon: An autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. A holon can be part of another holon.

Autonomy: The capability of an entity to create and control the execution of its own plans and/or strategies.

Cooperation: A process whereby a set of entities develops mutually acceptable plan and executes these plans.

Holarchy: A system of holons that can cooperate to achieve a goal or objective. The holarchy defines the basic

rules for cooperation of the holons and thereby limits their autonomy [2].

The PROSA Reference Architecture for holonic manufacturing systems [2] is a very inspiring paper from the late 1990-ies. It presents three fundamental types of holons: The *product holon*, the *resource holon*, and the *order holon*. In addition, a *staff holon* type was also included. These basic holon types manage different knowledge domains. The product holon has in its property knowledge about the product itself and the processes it undergoes. The resource holon consists of a physical part which represents the physical resource object, e.g. a CNC machine, and an information processing part representing the resource controller. The order holon is responsible for managing the physical product, its state model, and the transportation required for moving the product through the manufacturing system. From this it can be deduced that the amount of holons present in an industrial manufacturing system soon becomes considerable and the picture gets even fuzzier when these holons are expected to cooperate. As shown in Fig. 1, the type of knowledge shared between holon types can be described as follows:

- Order holons and product holons share production knowledge
- Order holons and resource holons share process execution knowledge
- Resource holons and product holons share process knowledge

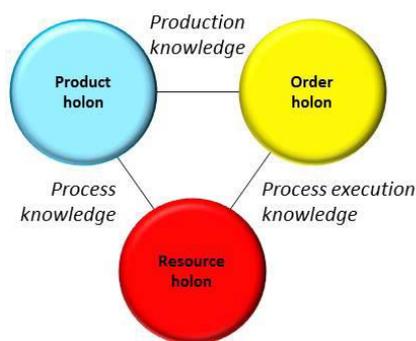


Fig. 1 Basic knowledge sharing holons

Holons can be aggregated or specialized as desired but on the lowest level of a manufacturing system the following associations can be made:

- The products holons represent the whole range of products which the system is capable of producing
- The order holons represent all the productions orders currently present in the system at any given moment of time
- The resource holons represent all the equipment units (machines, cells, tools, transporters, etc.) involved in the production

The rationale for applying a holonic manufacturing approach to shop floor control is driven by the hypothesis that distributed, autonomous control contributes positively to four operational effects:

- Resilience to disturbances
- Adaptivity and flexibility during system changes
- Efficient utilization of available production resources
- Dynamic management of mixed production

These four effects constitute a basic check list for pilot installations of holonic manufacturing systems.

The basic means for achieving these effects are:

- Holonification of the control system
- Small order sizes ('one-piece-flow')
- Dynamic process plans including alternative routing
- Negotiations between order holons and resource holons in each and every process step

These means have been cultivated in order to obtain the desired effects in the manufacturing system described in the next section.

2. Basic structure of the prototype implementation HolMS

The prototype implementation of a holonic manufacturing system, named HolMS, is the central part of the bigger Production Control System (PCS). A simplified structure of the PCS is shown in Fig. 2 (for details, see Fig. 6). HolMS has low-level interfaces to production resources, known as devices in HolMS terminology. Each device is 'wrapped' in a device driver which is a piece of software exposing data tags maintained by the device controller. The data are exposed through the OPC UA communication protocol.

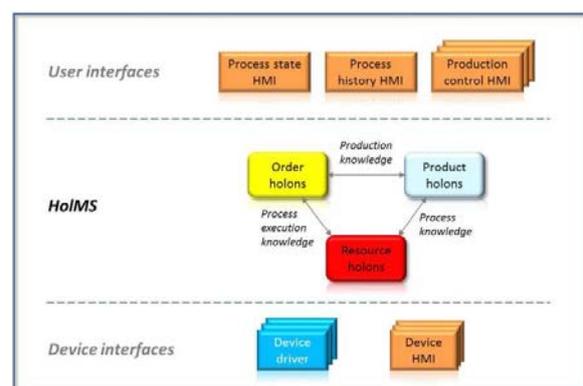


Fig. 2 Structure of PCS

At high-level HolMS has a set of HMIs (Human Machine Interfaces):

- Production control HMIs (one for each device represented) presenting the current state of the device
- Process state HMI presenting an overview of the current state for production process controlled by HolMS
- Process history HMI presenting historic values for a selected range of KPIs (Key Performance Indicators)

All high-level HMIs are web-based which means they are not physically tied to a specific location. The main motivation for this is to support a wide range of mobile devices for the operators.

Holons in HolMS communicate by messaging. The

messages are transferred via a framework based on ICE (Internet Communication Engine) from ZeroC, Inc. To reduce coupling between holons, communication is mostly implemented through the ICE topics system which is an implementation of a publish/subscribe pattern. Messages are published to topics and holons subscribe to selected topics to receive relevant messages. The structure of the communication is sketched out in Fig. 3.



Fig. 3 Interholonic communication

HolMS is a simple and straightforward implementation of the PROSA reference architecture with product holons, resource holons and order holons. The structure of holons is completely heterarchical.

3. The production segment target for the prototype installation

GKN Aerospace is a division of the GKN company and has facilities in more than 30 countries. One of these is GKN Aerospace Norway (GAN) situated in Kongsberg. In this facility a range of jet turbine parts are manufactured such as turbine shafts, turbine exhaust casings, and turbine vanes (Fig. 4). The low-pressure end of jet turbines consists of a ring of fixed guide vanes.



Fig. 4 Turbine vane. Photo: GKN Aerospace

GAN receives raw casted vanes from foundries and processes them into finished vanes ready for assembly by different major jet engine manufacturers (GE, Pratt & Whitney, Rolls-Royce, Snecma, etc.). These finishing activities include amongst others welding, marking, grinding, milling, electric discharge machining (EDM), soldering, coordinate measuring and fluorescent penetrant inspection (NDT).

In 2011 a project was launched as an Innovation Project for the Industrial Sector sponsored by the BIA program run by the Research Council of Norway. The primary partners were GAN as the end-user, SINTEF as R&D provider, and NTNU (Norwegian University of Science and Technology) as academic partner and with a few additional service suppliers. Quite early in the project the vane department was targeted as the production segment where a prototype installation of a holonic manufacturing system was aimed. The HolMS concept was a legacy from earlier SINTEF projects [3]. The vane department was characterized by time consuming machining processes, manually tended machining cells, mixed model production, long throughput times, large amounts of WIP, and manual transportation between production resources.

4. The Prototype Development Process

Plans were made for a stepwise development process with the final goal of letting a pilot implementation of HolMS communicate with a simulation model. This model was based on the visionary plans presented by GAN for the factory of the future with a horizon of five years ('the 2016 factory'). The first step in the process was to create a valid model of the 2016 factory running independently with simple cell controllers routing parts in a deterministic, cyclic way where alternative destinations were present, e.g. from weld milling to one of the 4 redundant Makino grinding cells. The next step would be to develop a bridging software enabling exchange of messages within the HolMS implementation to be recognized by components in the simulation model. The final step was to replace the cell controllers in the simulation model with HolMS resource holons allowing for dynamic, non-deterministic routing and, finally, to implement product holons representing the characteristics of the vane variants to be produced concurrently and order holons representing each individual vane present in the model. The intention of the planned development process was to demonstrate the applicability of the HolMS concept in a virtual environment. This would later become known as Pilot Demonstrator 1 (PD1). The simulation model in PD1 was developed with the 3DCreate package from Visual Components. The model reflected the presented plans for the 2016 factory with the following new features:

- One-piece flow
- Automated transportation
- Automated loading/unloading/fixation in machining cells
- Holonic Manufacturing Control

The mentioned bridging software (VC2HMS) [4] for communication between HolMS and the simulation model was developed by SINTEF. With this software, connecting the HolMS prototype and the simulation model, a simple testbed for the functionality and applicability of holonic manufacturing was established. However, it soon became apparent that a range of HMIs (Human Machine Interfaces) was required in order to track all the events and decisions made in HolMS during execution. Later, this recognition became a basic requirement in operation of holonic manufacturing systems: The non-deterministic and dynamic

characteristics of holonic manufacturing will require a lot of feedback information to the operators in order to have them understand what is going on in the system at any given point in time. A snapshot of the HMI-equipped PD1 is shown in Fig. 5.

Perhaps, the most remarkable feature of the HolMS implementation is the replacement of the traditional pull-based Kanban mechanism with a market oriented, push-based service request/service offer bidding mechanism. In this mechanism order holons with alternative destinations for the next operation send out a request for service to the resource holons representing the alternative destinations.

The resource holons return their individual service offers based on the current state of the physical resource, e.g.



Fig. 5 Pilot Demonstrator 1 with HolMS HMIs

operational state, queue length, etc. Then the requesting order holon evaluates the incoming offers and selects the resource with best offer for the next destination. However, experiments realized that there are many factors involved in such a request-offer process and that the rules governing the process have to be carefully 'calibrated' (ref. section 6).

With the success of demonstrating HolMS by PD1, both GAN and SINTEF were eager to take on the next natural step: To carry the HolMS implementation from the virtual space into the real world. This would take place by hooking up HolMS to the factory floor cells and demonstrate its functionality to the shop floor operators. The new demonstrator to be developed was called Pilot Demonstrator 2 (PD2). At the time of launching the PD2 development process, the plans on which PD1 were based were far from being materialized. In addition, a series of compromises had to be made in order to cope with operational constraints imposed on shop floor. For instance, one-piece flow and automated transportation had to be renounced upon. For these reasons the scope of PD2 was narrowed compared to the scope of PD1: The number of machining cells included by HolMS was reduced from 11 to 5. Much of the effort put into the development process for PD2 was concerned with development of OPC UA-based cell drivers to collect in real-time the necessary data from the shop floor equipment.

Another major activity was to establish a stable and reliable tracking system for orders based on RFID technology. Every active order on the shop floor had a RFID chip attached to it. Each machining cell was equipped with one in-buffer and one out-buffer. Each of these buffers had to be monitored

by RFID antennas in order to keep track of the orders inside. A lot of time was spent on achieving stability in these tracking arrangements as noise and clutter brought in trouble in a seemingly unpredictable way.

An outline of the system architecture of PD2 can be found in Fig. 6.

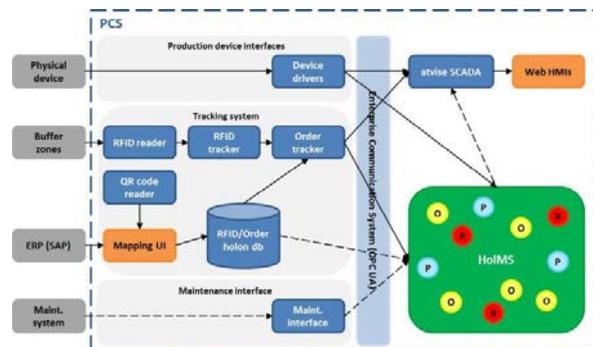


Fig. 6 Pilot Demonstrator 2 system architecture

The system architecture of the PCS consists of three functional parts:

- Interfaces to physical devices (machines and tracking system)
- Interfaces to external software systems (production orders from ERP and planned operations from the maintenance system)
- HolMS (the holonic manufacturing system prototype)

These three parts communicate over the Enterprise Communication System on a common OPC UA protocol.

5. Lessons learned

In this section the most important experiences of general interest from the development process are briefly summarized.

The Holonic Manufacturing paradigm is based on the idea of physical distribution. Machines and robots have their own intelligence and desires and cooperate to produce parts. Physical distribution has many advantages and is scholarly tempting. One could in theory fix one isolated component without breaking the rest of the system. This is however depending on low coupling between behaviors and interfaces something which is difficult to achieve. In practice modifying one holon often requires modifying other holons and physical distribution add one more layer of complexity and requires good and complex deployment solutions.

It is therefore tempting to centralize the holons implementation in one container, thus the central part of HolMS is installed on one PC and started with one script, although it can easily be physically split if required. The RFID sub-system, however is physically distributed.

A basic implementation represents only a starting point in the quest for the maximum effect of distributed, autonomous control. There are many factors contributing to the performance of the system and these factors should be parameterized for tuning purposes. One good example is the

parameters regulating the negotiation rounds between order holons and resource holons. There are rules for when a resource holon is allowed to return a service offer to a requesting order holon. For instance, when the in-buffer at a resource has reached a certain upper-limit length, the resource holon is prohibited from returning a service offer. A similar rule applies to the out-buffer. But it is difficult to predefine the values of these upper-limit parameters. It is also a pertinent question whether these parameter values should be fixed or dynamically tunable or even exists at all. In general, a holonic manufacturing system must be tunable to the shop floor on which it is imposed.

The development process of PD2 has shown that the amount of effort required for taking a verified system from a virtual context (simulation) to a shop floor context must not be underestimated. All the hardware and software components present on the physical shop floor are, generally, easy to represent in a virtual context as they are modelled with idealized behaviour and presence. In a shop floor context, however, things cannot be idealized any longer. Production resources from different suppliers have different controller technologies with different levels of data transparency. Older equipment cannot, for instance, be expected to have support for the OPC UA protocol. Physical machining cells can consist of several cooperating devices. Each device can have its own controller with an individual state parameter. How these individual states contribute to the overall cell state and how they shall be mapped into a cell driver, must be analysed carefully for each cell to be equipped with a driver before the cell driver software can be developed.

Equipment suppliers have widely different policies regarding exposure of controller data, and therefore ease of integration in a control system. This has been a time consuming and expensive issue at GAN. The lesson learned from this has led to a change in the general procurement specification. The original *'We need data, what can you offer'* approach is now replaced by a more formal requirements specification of a minimum set of data tags to be exposed.

The importance of carefully designed HMIs in autonomous and distributed control systems operated by humans must not be underestimated and may eventually represent the difference between success and failure. Because a holonic manufacturing system is a conglomerate of cooperating, autonomous holons, its behaviour is not only unpredictable at atomic level but may also appear as unreasonable to operators. These characteristics require that human operators at shop floor level are provided with, but not flooded by, the necessary information in order to get 'the big picture'. Exposing the wrong information details or through the wrong forms raises the risk for rising frustration to levels of neglect of cooperative system operation.

6. Next steps

Based on the experience from the development of PD2, GAN and SINTEF have agreed upon the initiation of a development process for a Pilot demonstrator 3 (PD3). The scope will be broadened by bringing in two additional industrial end-users: Nammo Raufoss and Benteler Aluminium Systems. A formal specification for PD3 has not

been defined yet but several ideas about new features have been proposed.

In the current implementation of the service offer negotiations the service requesting order holon operates with a time frame of 2 seconds from a request is issued to the evaluation of incoming offers starts. Offers from resource holons returned after this deadline will not be evaluated. If no offers have been received after 2 seconds a request for offers will be reissued every 10 seconds until at least one offer has been given. This relatively simple but rigid mechanism may be refined to a more flexible and less error prone version in future versions of HolMS.

While autonomy is motivated by robustness and adaptivity it will not necessarily ensure system-wide overall optimization which is taken care of by the traditional production plan. Functionality for combining both distributed autonomy and system-wide overall optimization [5] should be considered carefully.

Service offers are actually a calculation of the earliest starting point in time for order execution. This point is calculated from the sum of expected processing times for the orders already booked in on the resource plus the sum of setup times, if required. In order to make service offers richer and more in accordance with actual activity based costing, it will be considered to add cost attributes to resources in future implementations of HolMS. On the evaluation side, i.e. the evaluation criteria applied by the order holons, may also be subjects for redefinition.

Resource holons are allowed to give service offers under three conditions:

- Resource is not in failure mode
- Booking queue is shorter than a certain upper limit
- Out-buffer from the resource is occupied by fewer orders than a certain upper limit

Otherwise, the resource holon is not allowed to send service offers. A more sophisticated mechanism may be required and different strategies will be evaluated for the next generations of HolMS.

Van Brussel et al. [6] emphasize that resource holons must be designed to support 'low and late commitment':

'The workstation holons support explicit allocation of manufacturing resources. Examples of manufacturing resources are pallets, tools, storage space, pieces of raw material, machines, etc. These are allocated explicitly and with commitment as late and low as possible. This design choice enables, for instance, one workstation holon to lend, within the shortest possible delay, one of its tools to another workstation that has suffered a tool failure.' [6]

Currently, HolMS have no explicit mechanisms or parameters supporting low and late commitment, only indirectly through the already mentioned upper limits for booking queue lengths and out-buffer contents. A redesign may be required for such support but the full impact of applying the principle of low and late commitment have to be analyzed properly first.

As can be deduced from the quotation above, applying the principle of low and late commitment to its full extent may require a refinement of the structure of resource holons in order to support resource sharing. HolMS, in its current version, only have one level of resource holons representing a workstation or a production cell. Implicitly, these resource holons manage an internal conglomerate of devices including internal storage racks, handling robots, tooling, pallets, etc. An explicit representation of these devices by heterarchies or hierarchies of resource holons coordinated by meta-holons may be a consequence of applying the principle of low and late commitment.

In the current implementation, all orders are assumed to have the same priority. This is not the case as some orders are 'born' with a higher priority while other may acquire a higher or lower priority due to events such as maintenance, customer demands or higher level scheduling from the ERP system. Differentiation between order holons based on priority will have to be addressed in future versions of HolMS. There are many possible solutions to this issue. The simplest one might be to take into account priority in the negotiations. It might also be possible to add extra holons, for example representing maintenance, taking part in the negotiations.

Related to this reasoning is the question of when and how to reroute orders booked in for a failed resource. It is expected that such a mechanism can be rule based and that the rules must be parameterized as part of the system tuning.

Order holons are the most transitory of the three basic holons types. Due to this their history should be tracked and documented before they 'fade away' when leaving the holonic control area. This also facilitates detailed processing documentation which can support and even improve different QA procedures. This functionality can be implemented as a curriculum vitae database for order holons containing the entire processing history for each and every order which has been routed through the production system.

HolMS HMIs will most likely have to be enhanced and partially redesigned based on feedback from PD2 and also the release of the new ISA-101 standard for Human-Machine Interfaces [7]. This standard will be carefully studied in order to sort out which guidelines apply to the operation of HolMS.

In its current version HolMS is only connected to equipment and the ERP (SAP). The most serious defect in this respect is the lack of an interface to maintenance planning systems. Maintenance plans directly interfere with production plans and will almost always corrupt planned production. Scheduled maintenance implemented as mentioned above will require an interface to a maintenance planning system.

HolMS have currently only indirectly interfaces to the ERP system (SAP) through control software on device level, e.g. mapping of QR codes to order numbers. It has been a deliberate design choice to let HolMS run independently of

ERP systems. However, the future may reveal that direct interfaces are required.

Manufacturing Execution Systems (MES) are primarily applied for collecting and presenting data. Even though HolMS has its own HMI interfaces, there are good reasons for implementing a commercial MES in parallel with HolMS. Alternatively, HolMS integrated in a MES is also an interesting solution.

As a summary for the next steps it should be noted that a higher functional sophistication level increases complexity. In this respect, the benefits from implementing new or improved functionality must be weighed against the cost of maintaining a more complex system.

The methodology behind the prototype presented in this paper hopefully should be of interest for all sectors within material production characterized by mixed model production with shared resources.

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