Holonic Manufacturing Control: Rationales, Developments and Open Issues

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Abstract.

Holonic manufacturing systems promise to support a more plug-and-play approach to configuring and operating manufacturing processes, and thereby could underpin an increasing need for market responsiveness and mass customised products. This paper is concerned with the manufacturing control issues associated with holonic manufacturing systems. It addresses three key issues: Firstly, by examining current industrial trends and comparing this with a vision for what holonic systems should deliver, a clear business rationale is provided. Secondly, key developments in the area of holonic control systems are summarised and used to highlight both achievements and outstanding gaps in the research. This then leads to the final section in which a number of open issues in holonic manufacturing control are highlighted. In particular, barriers to the successful adoption of these methods are examined.

1. INTRODUCTION

The field of Holonic Manufacturing was initiated in the early 1990's [58,59] to address the upcoming challenges of the 21st century. It is intended to provide a building-block or "plug and play" capability for developing and operating a manufacturing system. Since 1990, an increasing amount of research has been conducted in holonic manufacturing over a diverse range of industries and applications. This paper introduces a vision for holonic manufacturing and assesses how that vision matches the current needs of manufacturing businesses. It then briefly reviews current research developments in holonic control systems and outlines a number of open issues that must be addressed before holonic control systems can be deployed industrially.

1.1 Background to Holonic Systems

The holonic concept was proposed by the philosopher Arthur Koestler in order to explain the evolution of biological and social systems [37]. He made two key observations

(i) These systems evolve and grow to satisfy increasingly complex and changing needs by creating stable "intermediate" forms which are self-reliant and more capable than the initial systems.

(ii) In living and organisational systems it is generally difficult to distinguish between 'wholes' and 'parts': almost every distinguishable element is simultaneously a whole (an essentially autonomous body) and a part (an integrated section of a larger, more capable body).

These observations led Koestler to propose the word "holon" which is a combination of the Greek word 'holos' meaning whole and the Greek suffix 'on' meaning particle or part as in proton or neutron. Suda's observation [59,58] was that such properties would be highly desirable in a manufacturing operation which is subject to increasingly stringent demands and faster changes. He therefore proposed a building block or "holon" based model for designing and operating elements comprising manufacturing processes similar in concept to the one outlined in Figure 1. Some key properties of a (holonic) manufacturing system developed from this model are:

- Autonomy – the capability of a manufacturing unit to create and control the execution of its own plans and/or strategies (and to maintain its own functions).
- Co-operation – the process whereby a set of manufacturing units develop mutually acceptable plans and execute them.
- Self-Organisation – the ability of manufacturing units to collect and arrange themselves in order to achieve a production goal.
- Reconfigurability – the ability of a function of a manufacturing unit to be simply altered in a timely and cost effective manner.

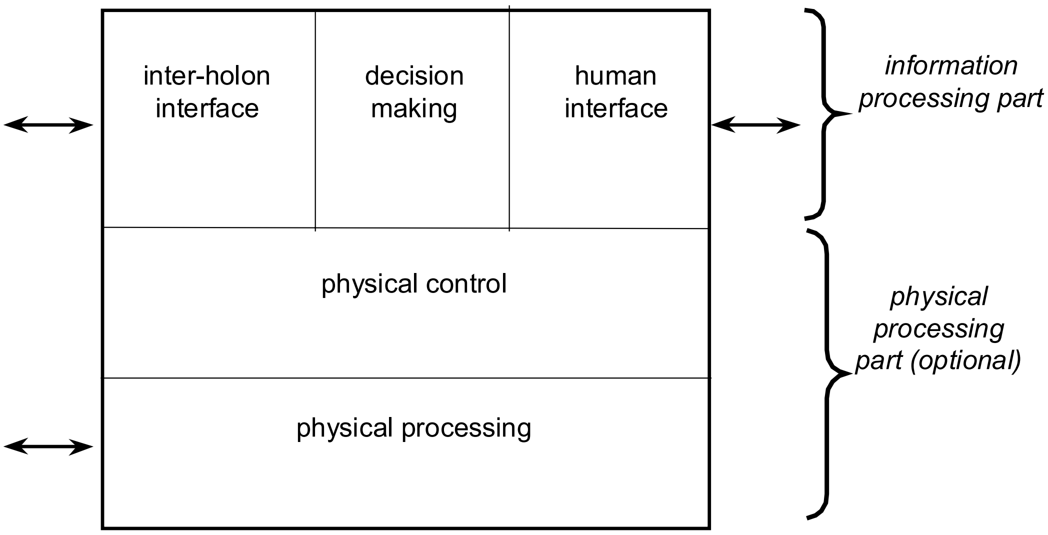

Figure 1 General Architecture Of A Holon [12]

1.2 Holonic Manufacturing Systems

We now provide some simple descriptions, definitions and examples of *holons* and *holonic manufacturing systems*. We define a manufacturing holon as "an autonomous and co-operative building block of a manufacturing system for transforming, transporting, storing physical and information objects" [17]. It consists of a control part and an optional physical processing part. (See Figure 1.) Hence, for example, a suitable combination of a machine tool, an NC controller, and an operator interacting via a suitable interface could form a holon which transforms physical objects in a manufacturing environment. Other examples of manufacturing holons could be products and their associated production plans, customer orders and information processing functions. A holon can itself also consist of other holons which provide the necessary processing, information, and human interfaces to the outside world. A "system of holons which can co-operate to achieve a goal or objective" is then called a holarchy [17]. Holarchies can be created and dissolved dynamically depending on the current needs of the manufacturing process.

Hence, the intention is that a combination of different holons is responsible for the entire production operations, including not only the production planning and control functions, but also the physical transformation of raw materials into products, the management of the equipment performing the production tasks and necessary reporting functions. In this case the set of holons is referred to as a holonic manufacturing system. A holonic systems view of the manufacturing operation is one of creating a working manufacturing environment from the bottom up. By providing the facilities within holons to both (a) support all production and control functions required to complete production tasks and (b) manage the underlying equipment and systems, a complete production systems is built up like a jigsaw puzzle!

Since 1990 there has been a significant amount of reported research and a wide range of publications produced that refer to control systems in a holonic context:

- **conceptual descriptions** - pertaining to a high level overview of the way in which holonic control systems might be structured and might function [17,47,49, 57,58,62,65,67]
- **specific architectures and operating methodologies** – providing detailed descriptions of the different functions of a holon and its interconnection with other holons and the way the holons operate. A range of architectures have been proposed in the literature – some more feasible than others [17, 30, 67, 45, 38, 50, 68, 63, 10, 12, 28,29, 66]. A number of authors have also developed algorithms, protocols and interaction mechanisms which underpin holonic operating methodologies [21,33,20,19,4,48,43,53,63,70,8,9,28,34,39,71,72,44]
- **simulated or prototype implementations** – are less prevalent in the literature and have generally been proof of concept level implementations as opposed to industrial implementations [1,28,29,65,36,4,31,32,66,43,60,61,62,26,15,14].

While this work has been documented faithfully, it has been in general difficult a) to arrange the different research activities into a single organised picture and b) to position this work in the context of existing work in related fields.

1.3 Manufacturing Control in a Holonic Context

Holonic manufacturing is an approach to defining and specifying manufacturing production systems and represents an alternative to *Computer Integrated Manufacturing or CIM*, as an integrating methodology for manufacturing computer control. In the same way that CIM has been a blueprint for the design and specification of *hierarchical, centralised* computer based operations in the past, Holonic Manufacturing represents a candidate blueprint for *distributed computer-based* manufacturing operations which support local decision making. (See [40] for a detailed comparison between CIM and holonic manufacturing.) We conclude this section by summarising some of the primary differences between holonic control solutions and their conventional counterparts. The table in Figure 2 lists the main differences between conventional CIM-based and holonic approaches to production control.

Hence, like CIM, holonic manufacturing approaches have already exploited and will continue to exploit many existing technologies and methods. For example, the manufacturing control approaches appearing in the holonic literature have many characteristics in common with existing developments in *heterarchical manufacturing control* (see, for example, Duffie and Piper 1987, Duffie et al. 1988, Dilts et al. 1991, Lin and Solberg 1992, Duffie and Prabdu 1994), *intelligent scheduling* (see Zweben and Fox 1994, Prosser and Buchanan 1994 and the references therein) and in *multi agent systems* (Bussmann 1998).

	Conventional Control Solution	Holonic Control Solution
1	Fixed layered, hierarchical architecture representing the different production control problems	No permanent hierarchy of control problems
2	Command/response mechanism provides the basis for the connection between different production control problems	Interactive interchange / simultaneous solution is possible between different production control problems
3	Predetermined solution format to individual production control problems	Solution format determined by the different holons involved
4	Typically a centralised solver for each individual production control problem	Typically a distributed solver, with co-operative interactions between nodes
5	Solutions time constrained by processing power	Solutions time constrained by communications speed
6	Control systems architecture effectively decoupled from control solutions	Control systems architecture tightly coupled to control solutions

Figure 2 Characteristics of Conventional and Holonic Control Approaches

1.4 A Simple Illustration for Holonic Manufacturing Operations

We will now demonstrate, via a simple illustrative example, how a holonic control system might function. This illustration is deliberately taken to the extreme in order to highlight some key elements of holonic manufacturing. Initially (referring to Figure 3), a holonic manufacturing system consists only of a pool of unorganised *resource* holons (RHs). Upon arrival of an order, an *order* holon (OH) is created which begins to negotiate with resource holons regarding the provision of certain manufacturing operations. During the negotiation process, the order holon demands specific properties required from the operation, such as high quality or high throughput, while the resource holons try to optimise their utilisation. At the end of the negotiation, the resource holons form the agreed manufacturing line (i.e. a manufacturing holarchy) and the order holon initiates the creation of *product or workpiece* holons (PH).

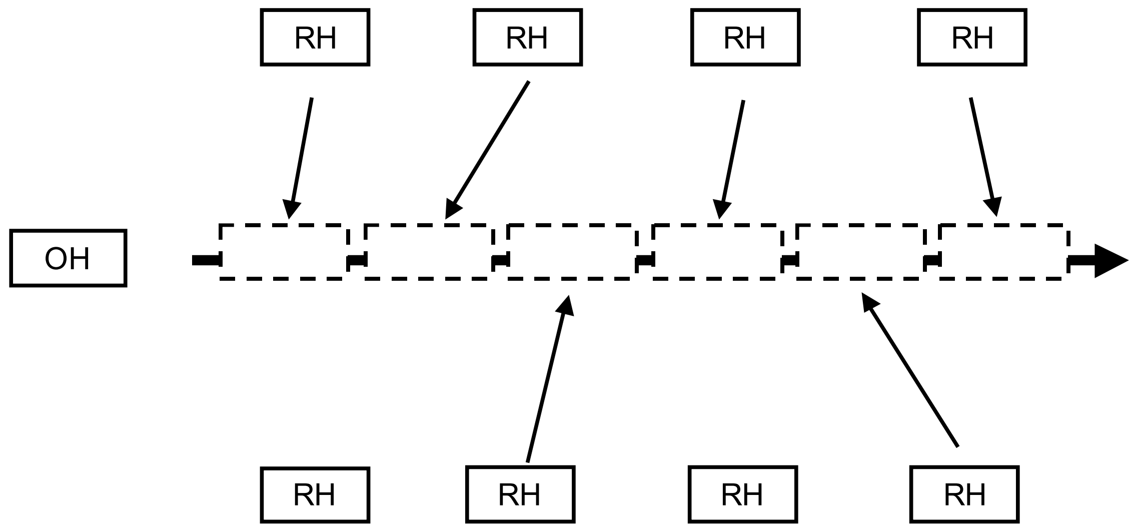

Figure 3 Self-Organisation of Order Processing.

The product holons enter the manufacturing holarchy (e.g., from raw materials stock) and immediately bargain for resources in order to get processed. Each product holon does so individually and focuses on the next operation(s). Once these operations have been performed at a resource, the product re-initiates the bargaining with holons representing the remaining (next) operations. The overall organisation of the resource holarchy – initially or subsequently negotiated between order and resource holons – assures that the product load is efficiently distributed over the available resources in order to achieve the global goals of this holarchy.

In case of a disturbance, the affected resource holon removes itself from the resource holarchy and goes to a repair booth. The remaining resource holons re-organise themselves in order to account for the capacity loss. From the point of view of the product holons, the processing continues as usual, only with fewer resource holons to negotiate with. After repair, the resource holon re-joins the resource holon pool again.

At the end of the order processing, the order holon is removed and the resource holarchy dissolves into the resource holons which then try to participate in new order holarchies.

2. MANUFACTURING REQUIREMENTS ANALYSIS

Manufacturing operations are not an end in themselves, but serve as a means to achieve the business goals of a company. It is therefore essential for an evaluation or comparison of manufacturing concepts to identify the requirements on the manufacturing process against which the concepts should be evaluated. These requirements are derived from the business goals and the given or expected market conditions. Business goals and market conditions, however, may change over time and thus the set of manufacturing requirements. A manufacturing approach that has been sufficient until now, may result in a poor performance in the future. Consequently, manufacturing concepts should not only be evaluated against the existing requirements, but also against future (possibly unknown) requirements.

This section therefore looks at the current business trends and shows how these will change the manufacturing environment. The new manufacturing requirements are then used to derive requirements on the control of future manufacturing systems. This process is outlined in Figure 4. (Note that there are other contributors to the manufacturing requirements that we will not deal with in this paper.) The manufacturing and control requirements identified will serve as the criteria for evaluating the manufacturing concepts in later sections.

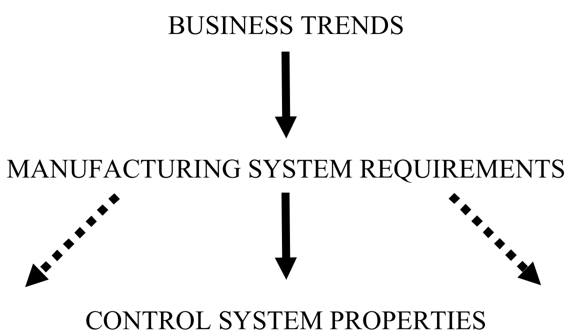

Figure 4 Requirements Break Down Process.

2.1 Business trends

It is difficult to estimate what the business requirements of the 21st century will be. The current requirements of producing goods of a specific quality at low costs will certainly remain in place. But the current market trends suggest that additional requirements will arise which will determine the competitiveness of a company and thus its survival in the next century.

Recently, the manufacturing industry has been facing a continuous change from a supplier's to a customer's market. The growing surplus of industrial capacity provides the customer with a greater choice, and increases the competition between suppliers. Aware of this power, the customer becomes more demanding and less loyal to a particular product brand. He demands constant product innovation, low-cost customisation, better service, and chooses the product which meets his requirements best. In combination with globalisation, these trends will even increase in the future.

The consequences for the manufacturing industry are manifold. Companies must shorten product-life cycles, reduce time-to-market, increase product variety, instantly satisfy demand, while maintaining quality and reducing investment costs. These consequences imply

- more complex products (because of more features and more variants),
- faster changing products (because of reduced product life-cycles),
- faster introduction of products (because of reduced time-to-market),
- a volatile output (in total volume and variant mix), and
- reduced investment (per product).

The effects can be summarised as *increasing complexity* and *continual change* under *decreasing costs*.

2.2 Manufacturing System Requirements

Most existing requirements placed on a manufacturing operation will still apply in the future. These include guaranteed performance, high reliability of equipment, quality assurance, cost minimisation etc. Given the trends described in the previous section, though, additional requirements will become relevant, if not predominant.

- **Increasing Complexity**

A major requirement will be to minimise the complexity of the manufacturing process (despite the likely increases in the variety of products and product ranges). This can be achieved basically by reducing the number of manufacturing system components and by standardising structure of these components and their interaction. Nevertheless, there is a limit to reduction and standardisation, as a complex product requires a certain set of complex operations.

The remaining process complexity must be mastered. This can be achieved on the one hand by creating an intuitive, self-explaining structure of the manufacturing (and control) system, and on the other hand by assuring a well-defined behaviour upon certain actions and events. Ideally, the control layer of a manufacturing system should be completely transparent to the end-user, and any actions or events should exhibit well-known effects on the overall system performance. In particular, the control layer should not introduce additional complexity and the overall behaviour of a manufacturing system should be well-defined under all circumstances.

- **Constant Product Changes**

Constant product changes require the re-use of existing manufacturing equipment. Buying new equipment is either too costly or takes too much time. Re-use of equipment implies the re-use of the units and the re-organisation of the manufacturing process.

Re-use of manufacturing units can be achieved either through flexibility of function or through reconfigurability. A unit is immediately re-usable if the new operations required are part of the range and mix of operations of this unit. High functional flexibility thus increases the chances of equipment re-use. Units equipped (up front) with a large range of operations, however, can be very costly. In contrast, the costs of a unit are often reduced considerably if the re-use is provided through manual reconfigurability. For monthly product changes, this is acceptable. Weekly or daily product changes, though, are likely to require instant unit flexibility.

An analogous requirement applies to process re-organisation. The manufacturing process must be either flexible or reconfigurable in order to deal with the product changes. In the former case, the manufacturing system is sufficiently flexible to change to the new processing steps. In the latter, the manufacturing system itself has to be re-organised in order to create the desired processing steps (including rearrangement of units and re-routing of parts).

- **Volatile Output**

The volatility of the demand forces the vendors to adapt their output to the market. A product sells only when the market demands it. If a company does not supply the right product at the right time, another company makes the deal.

As a consequence, the manufacturing system must be able to vary its production output. This implies scalability of the manufacturing system if the total volume changes, and inter-product flexibility if the product mix changes. Scalability can be achieved either by extending the working time or by adding more resources. Extending the working time is certainly limited to 24 hours a day and seven days a week. The ultimate measure to scale up the manufacturing operations is therefore to add resources.

Inter-product flexibility requires a re-assignment of resources which is similar to the re-use of equipment. Only in this case, the resources are re-used for existing, but better selling products.

- **Reduced Investment and Robustness**

The task of managing change becomes even more difficult if it has to be achieved at decreasing costs. A company might even decide not to provide full flexibility or reconfigurability if the costs are prohibitive. The real challenge is to manage change at low costs.

A low investment approach to change management, however, creates a second difficulty, namely that of disturbances. A behaviour which is achieved under scarce resources is vulnerable to (internal and external) disturbances. Future manufacturing operations will therefore require increasing robustness. Robustness can be achieved either structurally or dynamically. Buffers in terms of material or time slack provide structural robustness. System flexibility allows to adapt the process to failures, for instance by using spare resources or re-routing jobs.

2.3 Control System Properties

The requirements on the manufacturing system have also implications for the control of such a system. Many requirements can only be achieved if the control system meets equivalent requirements. Requirements like unit flexibility or reconfigurability are mainly hardware issues, but system responsiveness is certainly impossible without some kind of intelligent control. This subsection therefore looks at the consequences of the new manufacturing requirements for the control, regardless of the actual design and implementation of the control system.

I. The architecture of the control should be decentralised and product-/resource-based.

For even small manufacturing systems, a centralised approach to control is practically impossible. A single controller would be too complex, would become a bottleneck, and would be too difficult to change. There must be at least some kind of decentralisation.

Decentralisation, however, can take many forms. For instance, a system can be functionally or geographically distributed. But in order to allow for maximum flexibility, the decentralisation should be product- and resource-based. In a resource-based architecture, every resource contains all control capabilities necessary to process jobs. In particular, a set of resources is able to allocate jobs to resources without a centralised support. The advantage of the resource-oriented approach is that the system can be changed and scaled up fairly easily. Furthermore, the control corresponds in its structure to the manufacturing system and thus reduces the complexity added by the control system to a minimum. The control activities might even become transparent to the end-user. A similar argument applies to equipping orders and work pieces with the necessary control capabilities to get produced.

II. Control interactions should be abstract, generalised and flexible.

A resource-based control system is certainly easier to change and scale up than a centralised or functionally decentralised system. Maximum changeability, however, is only achieved if dependencies between resources are reduced to a minimum. If one resource is changed, but other resources heavily rely on exactly this resource and its specific behaviour, then the change of the single resource entails a lot of changes at other resources (which might in turn entail changes at even more resources).

Consequently, in order to achieve maximum changeability, resources should be de-coupled in three steps:

1. abstract interaction – make no assumption about the internals of other components
2. generalised interaction – make as few assumptions as possible about the other components' behaviour
3. flexible acquaintances and interaction – dynamically decide with whom and how to interact

III. *The control should be reactive and pro-active.*

In order to respond to short-term changes and disturbances, the control must be reactive. This includes the ability to recognise critical situations, make decisions about the reaction, and perform corresponding actions. In contrast to traditional planning and control approaches, the product- and resource-based architecture also distributes the planning capabilities since they depend strongly on the characteristics of the resources and the product. A resource for instance must also participate in the allocation of jobs or the sequencing of operations. As a result, the control must be reactive and pro-active at the same time.

IV. The control should be self-organising.

The need to adapt the manufacturing process in the face of changes or disturbances will not only affect the resources, but also the organisation of the manufacturing process as a whole. Obviously, in a highly responsive manufacturing system, the organisation must be responsive too and this responsiveness should emerge from any (re-) configuration of the resources and rearrangement of the process.

2.4 Connecting Business Drivers and Control System Needs

Figure 5 summarises the linkage between the business drivers and manufacturing requirements, where the link between different characteristics is indicated by an asterisk. Figure 5 also illustrates a linkage between the necessary manufacturing requirements and the specific needs this places on production planning and control.

BUSINESS DRIVER

MANUFACTURING SYSTEM REQUIREMENTS

	standardisation	minimal system structure	intuitive/ transp. structure	well- def./ transp. behaviour	flexibility	reconfigurability	scalability	robustness	
Complexity	*	*	*	*					
responsiveness					*	*	*	*	
distributed architecture			*			*	*	*	(I)
product/resource based architecture		*	*			*	*	*	(I)
abstract/ generalised interactions	*			*	*	*			(II)
flexible acquaintances / interactions				*	*	*	*	*	(II)
reactive capabilities				*	*			*	(III)
pro-active capabilities				*	*	*	*		(III)
self organising		*	*			*	*		(IV)

CONTROL SYSTEM NEEDS

Figure 5 Linking Business, Manufacturing and Control Needs

2.5 The Holonic Vision Matching Manufacturing Control Needs

The short description of the holonic vision of manufacturing in Section 1.4 has indicated that a holonic approach can address many of the requirements (I-IV) identified in Figure 5. The requirements are met because of the basic concepts that underpin the holonic approach:

- Holonic Structure – The holonic approach inherently proposes a distributed, product- and resource-based architecture for the manufacturing operations. (Requirement I)
- Autonomy – Each holon has local recognition, decision making, planning, and action taking capabilities, enabling it to behave reactively and pro-actively in a dynamic environment. (Requirements I,III)
- Co-operation – Co-ordination, negotiation, bargaining, and other co-operation techniques allow holons to flexibly interact with other holons in an abstract form. Because of the dynamic nature of the holarchies, each holon must employ generalised interaction patterns and manage dynamic acquaintances. (Requirement II)
- Self-Organisation – Holonic manufacturing systems immediately re-negotiate the organisation of the manufacturing operations whenever the environmental conditions change. (Requirement IV)
- Reconfigurability – Because of the modular approach, holons can be reconfigured locally once the inherent flexibility of the holons has reached its limit. (Requirements II,IV)

To summarise the degree to which holonic manufacturing control can, when fully developed, address today's needs for industrial control systems, the relationships between holonic characteristics and control system needs is overviewed in Figure 6

Control Requirements	Holonic Manufacturing
decentralised architecture	yes
product-/resource-based architecture	yes
abstract / generalised interactions	partly
flexible acquaintances / interactions	partly
reactive capabilities	yes
pro-active capabilities	yes
self-organisation	yes

Figure 6 Comparison of Control Requirements and Holonic Features.

The vision presented in Figure 6 appears promising in that it indicates that a fully operating holonic control system can achieve a number of the outstanding requirements for current and future manufacturing production control systems. However, this vision is still some way from being realised in practice. In Section 3 we will address the current state of holonic control system developments .

3. DEVELOPING HOLONIC CONTROL SYSTEMS

The prinicipal focus of this section is to review the development of algorithms which support holonic control systems. This is for two reasons

(1) To a certain extent algorithms supporting holonic control can be directly contrasted with those found in conventional production control environments. In Section 3.2 we compare different holonic control developments using a conventional view of production control.

(2) The existence of effective algorithms is an indicator of the degree of maturity of holonic research - without them it is not possible to assess the likely performance of a production operation running with holonic systems in place. In contrast, it is expected that numerous architectures for designing and implementing holonic control systems will continue to be proposed (as discussed in Section 1) and will also vary as information technology advances.

To begin however, we establish some common ground in the different systems architectures used in the algorithms that follow.

3.1 Developments In Holonic Control Architectures

In order to simplify the discussions that follow, we will assume a common description of a manufacturing process operating on holonic principles. In line with the holonic vision in Section 1.4, the process is assumed to comprise some or all of the following elements:

- ***Resource holon*** - a single unit comprising one or more physical processes or transportation resources, its control systems and any necessary human based operations.
- ***Product or Part holon*** - a unit comprising the physical product or part being produced and the human and computing support necessary to initiate and monitor the act of producing it.
- ***Order holon*** - a unit representing the requirements of a particular order, including information such as product qualities, due dates, costs, priorities. It may also encompass physical products in either a finished or unfinished state and / or information about order status.
- ***Co-ordinator holon*** - an optional support unit (computer or human based or a combination of both) providing a level of co-ordination between the different holons, and ensuring that the global goals of the factory are represented.

Each of these holons - once created - is assumed capable of a degree of local reasoning and decision making and an ability to communicate in an interactive manner with other holons. We will discuss the way in which these capabilities support different production planning and control issues in the next section. For more details on the overall descriptions or architectures of individual holons or their connection infrastructure systems, the reader is referred to [17, 12, 71]. For example, the so called *Product - Resource - Order - Staff Architecture* (PROSA) proposed in [68] has been widely used and more recently an architecture based only on the nesting of a *Product – Resource* model – the so called *Holonic Component Based Architecture (HCBA)* - has been developed [15].

3.2 Developments in Holonic Control Algorithms

This section intends to briefly summarise the current work relating to the algorithms deployed between holons in order to generate production control solutions. For more details the reader is referred to [47] in which a comprehensive review of holonic production planning and control is carried out.

We will describe how the current developments in holonic manufacturing apply to each of the control activities in Figure 7, (i.e. planning & scheduling, shop floor control & execution and machine & device control).

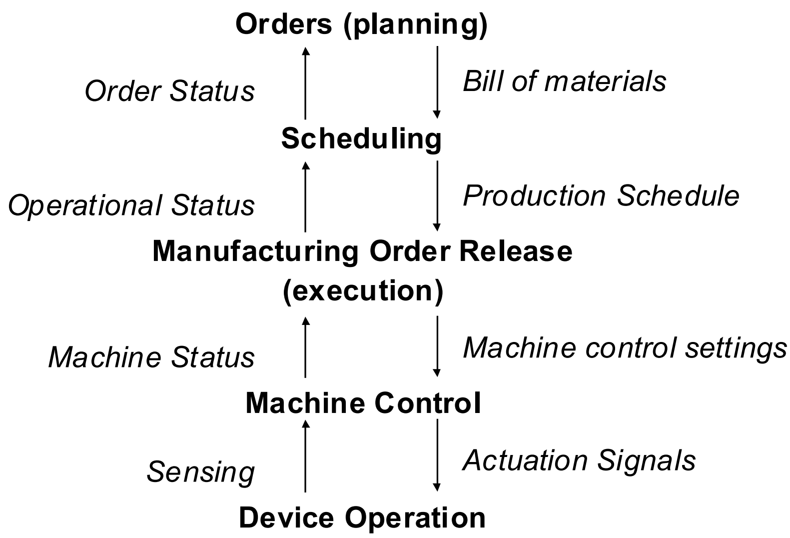

Figure 7 Typical Manufacturing Control Hierarchy

3.2.1 Planning and Scheduling

We restrict the following discussions on production planning to a) the decomposition of an order into a sequence of production operations and b) the nominal allocation of operations to resource types (but not to specific resources or times). Approaches to holonic planning typically involve a number of the following steps:

1. Each product holon performs a decomposition of the supplied product specification into constituent parts or sub assemblies.
2. For each product the manufacturing operations needed are identified (by the product holon).
3. The type of resources to provide operations needed are selected via interaction approach between product and resource holons.
4. An interactive process involving resource holons and product holons for determining a suitable set of operations.
5. A full make sequence (assembly plan) is finalised and this normally resides with the product holon

We note that this assumes - *a priori* - that the products required to fulfil an order have already been identified and also that either the product or the resource is co-ordinating the planning process. The benefits of a holonic approach compared to more conventional approaches are principally due to the distributed and interactive nature of the planning process, enabling new products and / or production resources to be introduced without major system alterations. The close connection between the individual holons and the physical resources they represent also enables planning to maintain a close alignment with the (dynamically changing) capabilities available on the shop floor. Holonic planning approaches have been reported in (28,29,30,20,21,4,31,32,55].

Similarly, we assume that scheduling simply involves a) the allocation of production operations to specific resources and b) the specification of the timing (start, duration, completion) for those operations. The key characteristics which typify a holonic scheduling approach are:

1. A local decision making and computational capability associated with each holon.
2. A co-operative interaction strategy which governs the way in which holons exchange information and determine mutually acceptable solutions.
3. An interchange mechanism or protocol which manages the exchange of the message types needed to execute the co-operative strategy.
4. A means of ensuring that the global concerns of the factory are addressed.
5. A degree of central co-ordination (not present in all solutions).

Some of the key themes to emerge from the work on holonic scheduling to date [53,28,29,43,60,31,32,50,1,11] have been

- A truly emergent approach to the development and execution of schedules vs a semi-centralised formulation in which distributed processes simply compute a result on behalf of a centralised coordinator
- the choice of an heuristic based vs distributed optimisation based decision making strategy – in the latter a degree of local optimisation is aimed for.
- the ability to closely interface the scheduling solution with shop floor execution control in order to be able to address dynamic rescheduling requirements

3.2.2 Execution / Shop Floor Control

Execution or Shop Floor Control involves the initiation, control, monitoring and termination of tasks and involves actual times and actual production settings. Within a holonic manufacturing system, execution is predominantly concerned with a) ensuring that the holon is capable of establishing and maintaining autonomous operations and b) that it undertakes tasks compatible with production requirements even in the face of disruptions. Execution has been addressed in the holonic literature by [27,31,32,66] where the autonomous behaviour of the (resource) holons in each case is managed by an internal model of the operations. Such a model is an essential requirement for the holon's self-management. The novel elements of a holonic approach to execution are that a) execution proceeds via a negotiated set of steps rather than a pre-determined sequence and that b) the resources (machines) executing the manufacturing operation are also responsible for the decisions made about the timing and nature of the execution. A further important issue is the relationship between execution and scheduling which has been discussed in [66,54].

3.2.3 Machine and Device Control

In a holonic system, machine control – which involves the initiation, co-ordination and monitoring of the different machine functions or devices required to support the execution of production tasks by an individual machine – has been largely treated as a conventional control problem coupled to a higher level holonic operation. (See for example [3,54,61,62,71].) The focus in these cases has been on achieving effective interfaces. Only in [51] is the possibility of a machine itself running on holonic principles truly considered where the interactions of the individual devices which constitute a machine are determined co-operatively. There has been even less work in the device area – that is, the actuation, sensing and feedback control of the physical operations which support a machine – but most of the above comments also apply.

Although developments in both holonic machine and device control have been limited to date, opportunities for greater flexibility and disturbance handling present themselves in the way in which trajectories and control actions could be negotiated to suit the current operational environment rather than following predetermined paths. One would expect such a system to be more adaptable to changing conditions arising, for example, from wear, damaged parts, faulty components or sensors.

3.3 Summary of Developments

The algorithmic developments outlined in this section indicate that a subset of elements required for the vision for holonic manufacturing systems outlined in Section 2 has been addressed. The concepts that were described as underpinning the holonic approach were structure (or architecture), autonomy, co-operation, self-organisation and reconfigurability. Numerous architectures for holonic manufacturing systems have been proposed, co-operative mechanisms have been explored to a degree within the different production control levels, and requirements for autonomy have been established, particularly with regard to the lower level control functions in Figure 7. However, apart from organisational aspects associated in holonic planning there has been little or no attempt to explicitly address the requirements for self-organisation which underpin the flexible response of a holonic system. In the next section we will summarise a number of outstanding issues in this field.

4. OPEN ISSUES

4.1 Open Issues in Holonic Production Control

There are a number of critical issues that must be addressed before holonic control solutions can be expected to play any significant part in next generation manufacturing production systems:

- **Analysis of the Performance of Holonic Manufacturing Systems:** A rather prominent weakness in the research to date has been the lack of any discussions about the relative performance of the control mechanisms that they support. In particular, holonic manufacturing systems are frequently cited as performing well in the face of disturbances but there has been little reported evidence of them being shown to do so. Any serious industrial commitment to holonic manufacturing systems in the future will require a demonstrated ability to *improve* performance beyond that of conventional systems. To be fully effective, holonic manufacturing requires a complete re-organisation of production operations, which is a costly undertaking. Therefore, it is very important to show and quantify the benefits as is done for example in [14]

- **Migration to Full Holonic Manufacturing Control Algorithms:** The review in Section 3 reflects a research activity that has to date aligned itself with the conventional control systems hierarchy in Figure 7. That is, distributed, co-operative solutions have been sought for each of the individual problems on this hierarchy. Few authors however, have truly attempted to question the relatively static *command-response* connections between these layers. These current developments are illustrated in 8(b). It is the authors' opinion that a new more holistic approach is required for the control of manufacturing operations, which seeks to achieve co-operative interaction *across* these layers as well as between elements *within* them. For example, a separate planning and scheduling phase is in fact restrictive, because planning can commit an order to a particular make sequence when in fact more than one may be possible and each option may be more or less desirable depending on the current plant state. Hence combining planning and scheduling may be highly attractive, at least if planning options are not deleted until scheduling is considered. A distributed and interactive approach to *combined* planning and scheduling, or *combined* scheduling and execution or even *combined* execution and control should present a relatively straightforward migration from the current state of development. (Refer to 8 (c)). From these combined solution approaches, the next migration step is to consider systems which support comprehensive manufacturing holons which may seamlessly integrate all of the five control functions into their operations (8 (d)).

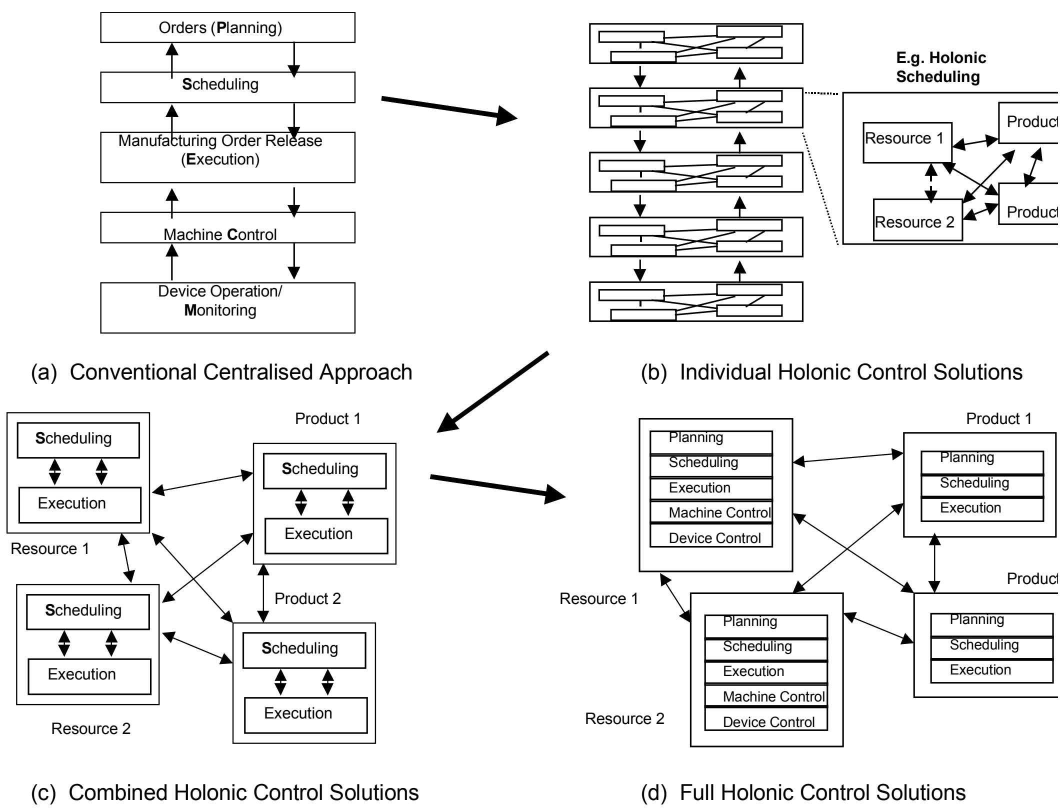

Figure 8 Migration to Holonic Control Algorithms

- **Establishing Suitable Implementation Architectures Compatible with Existing and Future Commercial Computing Systems:** There has been little or no work done in determining the compatibility of the holonic vision with the current or the next generation of industrial control and computing systems. Holonic systems will require a high level of reasoning and computational capability at the shop floor levels, coupled with more flexible communications and more dynamic interfaces to human operators and users. Determining how to construct and implement systems architectures capable of fully supporting holonic operations while still operating with existing legacy systems will also be a major issue as holonic systems capabilities reach industrial strength. In the shorter term, suitable migration approaches for the implementation of intermediate holonic control capabilities are required (See, for example [16,27]) and effort is required to ensure systems vendors can access and adopt these approaches.
- **Establishing Suitable Standards for Holonic Control Systems:** Before any industrial confidence in Holonic Manufacturing Systems can be established, a comprehensive set of standards is required for the open specification of communications, data formats, systems architectures, algorithms and interfacing of holonic systems. Apart from work on the PLC-based IEC 1131 standard which examines the compatibility of holonic system with PLC programming languages there has been no comprehensive study of the implications for standards in this area.

4.2 Other Applications for Holonic Control Systems

Holonic Manufacturing has almost exclusively focussed on production applications within the discrete manufacturing domain. We note that there is considerable potential for applying the same approaches within other application domains:

- **Process Control Systems Based on Holonic Principles:** In [18] it is noted that process industries today form a major part of GDP within the economy of any nation. In general, they cover a very large and diverse sector of industries including petrochemicals, polymers, bulk and specialities chemicals and related utilities sectors. Historically, these processes have evolved from small scale, simple units, which were often operated in batch or semi-continuous mode. Energy and primary raw materials were relatively available plentiful. Large and attractive profit margins were the basis on which they have grown at such a rapid rate. Over the last two decades, however, this sector of manufacturing has also experienced an important change due primarily to increasing energy costs and increasingly strict environmental regulations. Growing competitive markets demanding so-called *mass customization* of products and rapid technological innovations are replacing the old style of mass production and *copy-cat* type R&D structures. There is also now a growing emphasis on improving efficiency and increasing profitability of existing plants rather than creating plant expansions. In a similar manner to section 2 of this paper, a set of rationales in developed for applying *holonic manufacturing* principles as a technological solution to the growing business concerns in chemical process industries. The anticipated benefits from holonic approach stem from the use of a distributed control systems architecture that supports flexible unit operations to dynamically integrate and collaborate with others as and when the production conditions change.

- **Holonic Manufacturing Applications in the Supply Chain:** We finally note that the restriction of holonic control applications to production applications alone is rather artificial and a consequence of the origination of this movement from within the production control community. Holonic control concepts are applicable in any circumstance where there is benefit to be extracted from an increased level of autonomous and distributed decision making which is closely aligned to the physical resources that will execute the actions resulting from these decisions. We note that a number of applications in supply chain logistics clearly fit this description.

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