In Proceedings of ASI' 95, Portugal, June, 1995

HOLONIC MANUFACTURING SYSTEMS IN CONTINUOUS PROCESSING: CONCEPTS AND CONTROL REQUIREMENTS

Duncan C. McFarlane

Industrial Control Centre, University of Westminster
115 New Cavendish Street, London, UK, W1M 8JS
email: mcfarld@westminster.ac.uk6

ABSTRACT

Holonic manufacturing refers to a modular approach to constructing and operating a manufacturing process whereby individual production units have the properties of autonomy and co-operation. This paper examines some key ideas behind holonic manufacturing in the particular context of continuous production processes. The main objectives of the paper are:

(1) To review the status of Computer Integrated Manufacturing (CIM) and use this as a basis to introduce some of the main rationale, functions and purpose for holonic manufacturing. It will be demonstrated that holonic manufacturing is a methodology equally applicable to continuous and discrete process domains.
(2) To demonstrate a unifying framework for control and diagnosis problems at all levels of a production environment which can be used in a holonic manufacturing model.
(3) To illustrate these control and diagnosis approaches in the context of a steel mill cooling control problem.
(4) To outline a number of outstanding research issues associated with holonic manufacturing systems

1. INTRODUCTION

Holonic manufacturing systems have recently been investigated as a possible solution to some of the problems experienced with using existing systems based on CIM (Computer Integrated Manufacturing) architectures. These problems have arisen in attempting to meet increasingly complex and variable market and production demands (Such demands are well outlined in a recent Economist article[1].) A holonic manufacturing system comprises functional units of manufacturing called holons - units which display the dual properties of autonomy and cooperativeness. It is proposed that a manufacturing process constructed from these units will exhibit many desirable properties including flexibility of production, easy reconfigurability and relatively high tolerance to process faults and variations.

This paper examines the development of automation systems in continuous and discrete manufacturing, the original motivation of CIM architectures and some of the current shortfalls experienced Within this context, the likely impact of holonic technologies on manufacturing systems in the future will be discussed. The influence of developments in areas such as autonomous agents[2,3] distributed communication systems[4,5], decentralised control, object oriented programming[6] and model based diagnosis[7,8] on these technologies will also be demonstrated. It is argued that holonic systems provide a framework and methodology for combining these and related technologies into an integrated yet modular operations hierarchy.

In particular the key issues in holonic manufacturing that are likely to impact on control systems theory and design are outlined, in terms of both architectural requirements (in comparison with those in existing systems) and algorithmic requirements. An abstract systems theoretic approach[9] will be used to examine these problems in a unified framework and demonstrate links with conventional control theory. Opportunities for an integrated self-diagnosis capability are also examined.

Finally, the paper will examine an manufacturing in the continuous processing industries via a model developed in[10, 11] for holonic manufacturing systems in a steel rod rolling mill. Options for process set up, control and diagnosis within a holonic context will be illustrated for this problem and it is shown how the requirements on autonomy and co-operation can be met in each case.

2. REVIEW OF AUTOMATION IN MANUFACTURING

This section provides a perspective on the background which has motivated holonic manufacturing as a possible methodology. It is not in any way a complete summary of automation in manufacturing, providing merely a perspective of trends and problems associated with current systems.

2.1 Manufacturing Automation in Continuous and Discrete Processing

Automation for manufacturing in the discrete and continuous domains has developed for different reasons and, because of this, the current range of commercial manufacturing systems solutions are divided between these domains. In discrete manufacturing, particularly the automotive industry, the PLC (Programmable Logic Controller) has been the fundamental unit of automation. Developed in the 1970's, the PLC provided a replacement to hardware relay circuits for the automation of sequential handling and machining tasks and the provision of reliable input/output facilities to support higher level scheduling and inventory computers and their underlying algorithms. The PLC has now evolved to the extent that the modern PLC provides most of the features of a powerful PC, excellent user interfacing, on board memory and specialist processors. In continuous or process-based manufacturing the key role in

manage complex processes rather than for the reason of automation, and in fact many of the early solutions were more centralised than distributed, in order to take advantage of large VAX or mini-computer capabilities. Current DCS

between solutions based on a DCS approach and a networked solution involving multiple PLCs with some form of integrated co-ordination function.

products through a range of production routes. In contrast, in continuous processing, the control of complex multivariable processes has provided the greatest challenge although higher level plant wide optimisation in

commercial systems literature.)

there is clearly some merging of hardware and techniques occurring, and in this paper, we will present a mechanism

2.2

The basic concepts and details of CIM are well understood and the reader is referred to a number of excellent [12 13 14 15]

CIM was originally intended to provide a standardised methodology for integrating commercial, design and

continuous and discrete domains and provides a unifying framework for the developments discussed in Section 2.1.

designed to support the business objectives of CIM. (Variations on this diagram predominate in the literature and from

system are stated along with typical computing requirements associated with each of these levels. (The equally

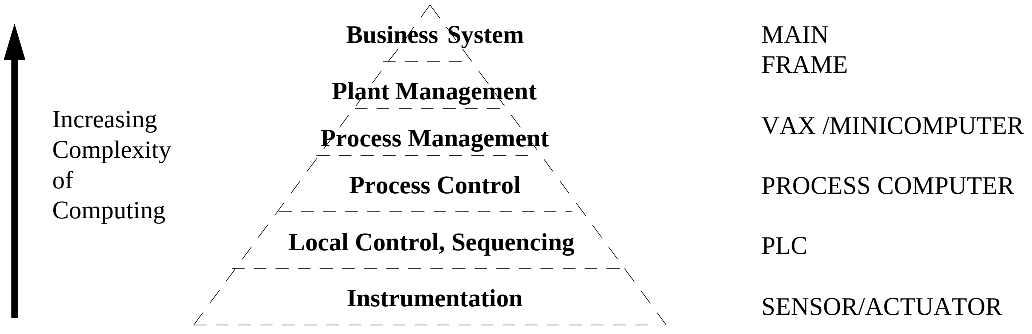


Figure 2.1 Levels of CIM architecture

From the perspective of this paper, some of the key features of CIM based computer architectures [12,13] are:

- **Common information networks -** at process and subcomponent levels, enabling relatively straightforward interchange of information and integration / co-ordination of functions at similar process levels.
- **Centralised Control Unit -** single point access to system controls enabling a remote location for operator stations
- **Reduced Human Intervention -** human access restricted to Level 3 and above in order to reduce variability in operations. Removing operational personnel from the production floor limited access to lower level machines and utilities to electrical and maintenance workers. One of the early ideas behind CIM was the concept of a "lights out" factory with no operational personnel in the production environment.

---

[i] Rehg [13] categorises five types of production operations: project based, job-shop, repetitive, line production, continuous in terms of CIM solution requirements. This work is principally focusing on the latter two.

- **Fixed position hierarchy -** the standard structure in Figure 2.1 is a hierarchy of increased computing complexity and power. Communications flow is “dictatorial” in the sense that commands flow down and reports flow up with little interaction.

- “**Advanced control**” **-** from a control perspective the so called advanced (model based) control and local scheduling or set up techniques are typically at process computer level, providing PLC setpoints across a serial or ethernet link to local controllers.

- **Standards -** for communications, programming and architecture

The necessary development of standards for architectures, functions, interfaces and programming and the growing complexity of production requirements has led to problems with CIMs ability to meet rapidly changing business goals. Some of these problems were recently outlined[16] and include

- **inflexibility** - The CIM hierarchy is fixed regardless of changing production requirements
  - It is difficult to expand/reconfigure a process for new products
- **robustness** - Performance is not guaranteed (and often not achievable) outside preset operating range
- **maintenance** - Difficulties with fault diagnosis as machine data is often inaccessible
  - Human exclusion from low level systems

In essence, computing systems in manufacturing have evolved into a separate business of their own with prescribed rules and structures that are independent of the production environment and the business goals to be addressed. The holonic methodology is an attempt to integrate computers, people and machines into a single function manufacturing unit capable of adjusting to varying production demands as they occur.

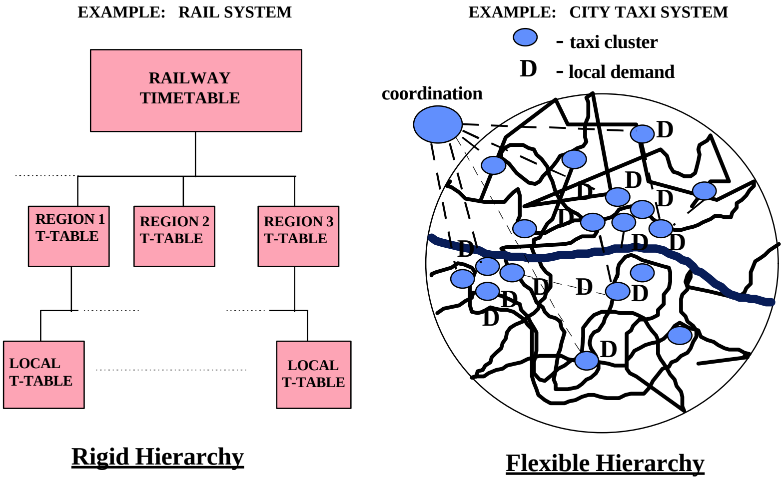
This development is not occurring in isolation, as improving hardware capabilities are making an increasingly large range of system configurations possible and reconfigurable.

3 HOLONIC MANUFACTURING

In this section we will briefly introduce holonic manufacturing and illustrate a functional system architecture to support this approach. The remainder of the section will then review some of the key support technologies that are required to underpin holonic manufacturing. It is important to emphasise here that holoni manufacturing does not represent a new technology - more correctly, it represents a novel integration methodology for a number of existing technologies.

3.1 Concepts in Holonic Manufacturing

The idea of a holon is credited to Koestler[17] who examined hierarchical behaviour within social and biological systems. He noted that complex situations or tasks can often be broken into a number of reasonably self contained sub tasks, which in turn could be broken into further sub tasks, defining a complex functional hierarchy. He observed that these sub-elements followed the so called Janus Principle, whereby the element is at once both a co-operating sub-element contributing to a larger task and a relatively autonomous element achieving its own sub-goal. A further key observation in examining social systems of this form is that different groupings of elements (people in this case) occur in order to solve different tasks. In other words the hierarchy was based on functional (or behavioural) requirements not physical structure. Figure 3.1 illustrates simplisticly the difference between a rigid (physically structured) hierarchy and a flexible (functional or goal seeking) hierarchy, whereby the rail time-table is set independently of any daily/weekly/monthly variations while the taxi system in a major city essentially follows the demand for its use (within reason!).



Rigid Hierarchy

Flexible Hierarchy

Figure 3.1 Comparison of Rigid and Flexible Hierarchies

Koestler therefore proposed the term *holon* to refer to elements reflecting this dual property of autonomy (from the Greek *holos*) and co-operation (from the suffix -*on*, meaning *part of*).

It is important to note that, in industrial situations, such functional hierarchies fundamentally lead to a *behavioural* or *goal seeking* description of a process rather than a structural or hardware oriented description. Intuitively, such a description appears well suited to developing manufacturing systems which can adapt readily to changing business goals. Additionally, such a framework - independent of physical structure - can provide a unified description of both discrete and continuous manufacturing environments.

3.2 Holonic Architectures

The 1993/94 Holonic Manufacturing Systems Test Case generated a number of candidate structures for holonic manufacturing (see [16] and the references therein). Figure 3.2 illustrates a version of the architecture initially proposed and motivated by Allen Bradley[18] and amended in a joint Test Case project between BHP (Australia) and Rockwell (USA)[10]. The key features of this architecture[ii] are

- any functional unit (holon) has a fundamental set of properties, reflected as supporting sub-units or sub-holons.
- the architecture supports a function based hierarchy with no reference to hardware/software platforms
- Figure 3.2 is a theoretically repeatable structure and can be applied at any level of the manufacturing process -i.e. all units are self similar.
- the architecture is clearly linked to object oriented design, with a parent structure providing many inheritable features

---

[ii] The architecture proposed in [18] also displays many of these features - the principal difference being the control systems focus in [18] compared to the manufacturing function emphasis [10] and in Figure 3.2

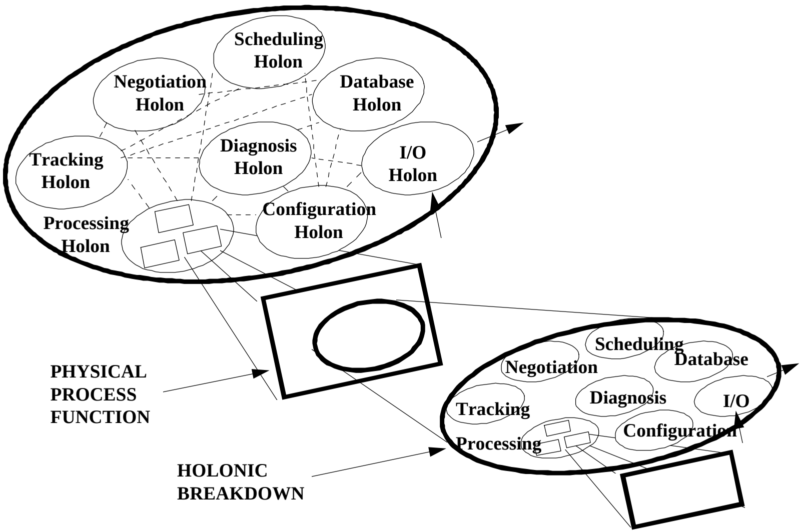


Figure 3.2 Proposed Holonic Description - BHP/Rockwell 1993/94[10]

It is important to realise that holonic units described in Figure 3.2 comprise part or all of the manufacturing function. The unit is responsible for providing all the services needed to perform a specified transformation of materials, information and/or energy. That is, the unit comprises not only the computer systems required to support the transformation, but also the machinery and any necessary human interventions and interfaces.

3.3 Background Technologies

As discussed earlier, holonic manufacturing, if successful, will draw on a range of different technologies. Some key influencing fields and technologies are summarised next.

(i) Communication & Computer Systems Theory

The development of distributed operating systems over the last five to ten years has led to the development of a range of algorithms that could be used to provide co-ordination and/or co-operative properties within holonic manufacturing. Holonic manufacturing will see a trend away from command driven manufacturing, with more local decision making being performed by negotiation between neighbouring production units and only limited co-ordination (if any) as depicted in Figure 3.3.

Figure 3.3 Command driven Vs Co-operation via negotiation

Possible algorithms include election, mutual exclusion or contract bidding which have their origin in communication network theory [4] and provision for the necessary extensions to communication protocols have been examined [5]. Additionally, much of the existing standards work in the manufacturing field has and will continue to be led by similar developments in computer system standards.

(ii) Autonomous Agents

Autonomous agent methods have developed in a range of applications including discrete machining, transport systems, and computer resourcing to enable more autonomous sub-tasks to be performed [2,3]. The method allows each unit a high degree of freedom for carrying out local tasks but with a central co-ordinator to distribute tasks and co-ordinate the results. The additional capability intended for a holon is the ability to negotiate with other holons and perform tasks co-operatively if appropriate.

(iii) Decentralised Control

Decentralised control algorithms have developed to handle the co-ordination of systems whose components are widely distributed - mostly in a physical sense [19,20]. Typically such algorithms will enable local control actions to be carried out with reduced or restricted information flows to and from a central co-ordination function. In contrast, a holonic system need not be distributed physically (rather functionally) and the ability of a control action to adapt to its surrounding environment must be incorporated.

(iv) Abstract System (Cybernetic) Theory

Clearly missing from work in holonic systems to date is a systematic mathematical framework for analysing holonic functions. As will be discussed in more detail in the next section, Abstract System Theory[9] provides a unified theory for analysing complex systems and provides a possible system theoretic framework for holonic systems. The features of such systems are:

- they provide analysis tools for goal seeking (acquired) as well as structural system models
- concepts of cohesion / interaction / co-operation can be evaluated
- graph theoretic tools are available for selecting functional groupings which can be used to define appropriate clustering of holons into higher level holons.

(v) Model Based Diagnosis

One of the key properties of a holon will be its ability to not only function as part of a process but to be responsible for its own well-being - that is have a self-diagnosis function. All fault diagnosis is based either implicitly or explicitly on the comparison of observed behaviour with a predetermined model. This subject is addressed in detail in numerous texts[7, 8, 21]. Self diagnosis involves integrating the diagnosis function within standard system operations, and the fundamental implication for holonic systems is that each holon must contain a model replicate of its own behaviour for diagnosis purposes.

Finally, it is also appropriate to note that several other manufacturing paradigms with some common features to holonic manufacturing have previously been proposed: Warneke[22]proposed a *Fractal Factory* incorporating a repeatable nested structures approach, and Van Brussel[23] provides a good summary of behavioural methods in manufacturing such as *Bionic Manufacturing* (cell - enzyme model) and *Genetic Manufacturing* (using DNA and brain neuron learning).

4. REQUIREMENTS FOR CONTROL AND DIAGNOSIS

The initial one year feasibility study into holonic manufacturing examined a number of case studies and stabilised that co-operative control (in the broadest sense) and internal diagnosis were two of the key requirements for a modular, semi-autonomous, interacting production unit.

4.1 Holonic Control Systems

In the previous section, a generic structure for a holon was proposed that is applicable to manufacturing functions at any level of the production hierarchy. (Refer to Figure 3.2.) In this section we examine specifically the requirement for control and demonstrate a framework that is compatible with this multi-level approach. Firstly, note from Figure 4.1 that control problems of both an static and dynamic nature occur at every level of the manufacturing problem.

LEVEL	**TYPE**	**STATIC**	**DYNAMIC**
Local Control	**Continuous**	**Model-Based Set Up**	**Model-Based Control**
Process Control	**Discrete/ Continuous**	**Schedule**	**Dynamic Rescheduling**
Process Management	**Discrete**	**Production Planning**	**Dynamic Planning**

Figure 4.1 Static and Dynamic Control Problems on Different Manufacturing Levels

Although the algorithms and problem domain are clearly different, in each case there is a clear problem of regulating a control variable via feedback in order to align an output variable with a desired setting. Within a holonic context, the key unifying requirement in all of these different static and dynamic control algorithms is that they be goal seeking - that is, the control algorithm should be provided with a set of requirements (linked to a task or sub-task) and must first convert these (high level) requirements into a solvable problem before solving the problem.

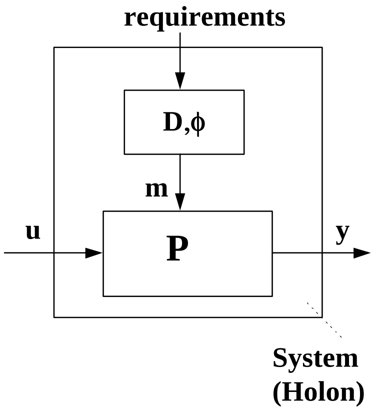


Figure 4.2 Control framework to support "goal seeking" requirement for HMS

The goal seeking system[9] depicted as in Figure 4.2 has the feature that it internally converts goals or requirements into an allowable set of parameters or trajectories of behaviour via some form of decision function, D. The actual control action is then carried out in process P. The terminology in Figure 4.2 is as follows:

P - process (+ model + controller)
D - decision problem
ϕ - decision principle
M - set of alternate decisions
U - set of alternate events
Y - set of possible outcomes
$m \in M, \quad u \in U,\ y \in Y$
$P: M \times U \rightarrow Y$

The development of appropriate (and flexible) decision problems is the key to embedding control activity within holonic systems whose goals may differ depending on the environment that they operate in. It is clear from the test cases[16] that a distributed optimisation based decision principle is well suited to holonic systems, and the goal-seeking methods could help with the integration of complex optimisation based control algorithms into manufacturing operations - a relatively uncommon event at present.

Figure 4.3 shows that an H_∞ type algorithm[24] is naturally suited to a goal seeking framework. The decision principle, ϕ, is the minimisation of the H_∞ norm of a cost function, which is generically denoted by

$$f = \inf_{K\ stabilising} J_\infty = \inf_{K\ stabilising} \left\| \left[F_L \left(M(G, W), K \right) \right] \right\|_\infty$$

where G is a model of the process or function to be controlled, W appropriate weighting for the cost function, M denotes the so called H_∞ standard plant combining the weights, process model and interconnections, K is the controller to be designed and $F_L(\cdot)$ denotes a Linear Fractional Transformation combining these elements to form the cost function. The decision problem, D, is that of selecting appropriate optimisation weights to reflect the global requirement and determine an appropriate set of controllers which satisfy this requirement. Hence referring back to Figure 4.2, the "process" P encapsulates the real process, a model of itself and the selected feedback control.

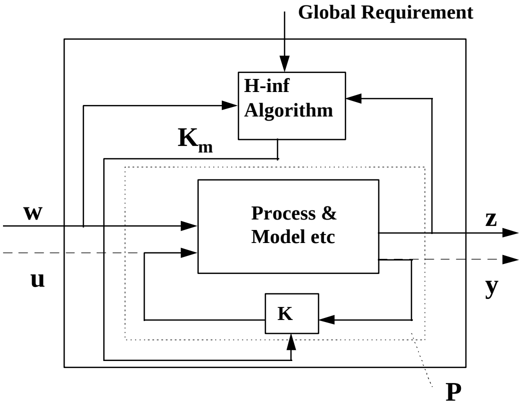


Figure 4.3 H_∞ type algorithm in Goal Seeking Framework.

As an example, the global control goal for a holon at the local or process level might be to achieve a target setpoint within 1% at steady state (frequencies below 0.01 rad/sec), with the additional constraint that the process model (denoted G) embedded in the holon is only guaranteed to be accurate to within 10% of true process behaviour (at high frequency where several dynamic modes are neglected). The decision process must produce a controller K_m from the class of feasible controllers K that will achieve this goal. Mathematically, this specific problem is referred to as the *mixed sensitivity problem.* [24] Note that some form of expert decision making for selecting weights is an integral part of such a goal seeking control function.

4.2 Requirements for Diagnosis

Holonic systems require a built in diagnostic capability in order to maintain their autonomous behaviour. The two key aspects of this capability are the requirements for a holon to detect and diagnose problems internally or if necessary by co-operating with neighbouring holons.[iii]

Detection involves the signalling but not necessarily the tracing of a problem in the holonic system. The method proposed for a holonic environment is the use of a *health status*[10] submitted by each holon to indicate normal operation or (potential) problems. The health status is the outcome of a local fault detection within the holon which could be solved by a variety of instrument or analytic (model based) redundancy approaches[7, 8, 21] each of which is a fundamentally a comparison between actual behaviour and ideal behaviour as predicted by a model. (It is precisely by comparing operations to internal models that we determine the health status.) All holons calculate a health status and submit this status to a local diagnosis holon. The health status is typically a value ranging from 0 to 1 (relating to the degree of model mismatch), where 1 indicates no faults, whereas 0 is completely unavailable for use. At the detection of a fault, the diagnosis holon then initiates an interrogation procedure calling on health statusses from all holons to form a fault signature (Figure 4.4) and if necessary extend this interrogation to the holon sub-levels. This is shown in Figure 4.5. In practice, it is unrealistic for cost and configuration reasons to assume that any single holon will have a sufficient number of sensors to enable it to isolate every fault condition. Note that by *sensors* we also include *virtual sensors*, whereby a signal can be reconstructed using internal holon models and values inferred or calculated from other real/virtual sensors. Further, also associated with each sensor is a degree of confidence (ranging from 0 to 1) indicating the reliability of the reading. In general, several holons will need to co-operate in identifying the cause of anomalous behaviour which is designated in Figure 4.4 by a ? health status.

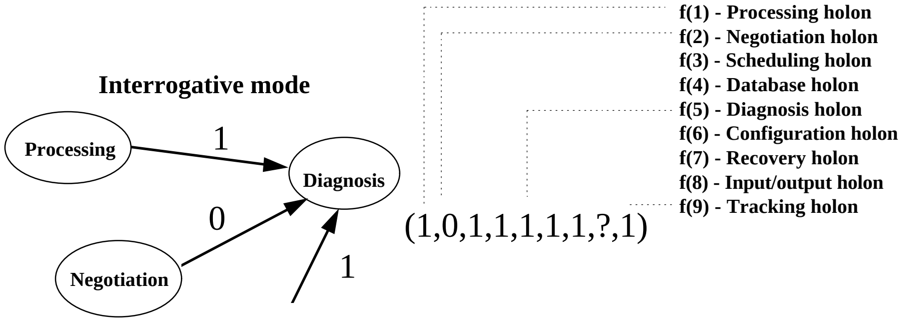


Figure 4.4 Interrogation using Health Status Concept to form Health Signature

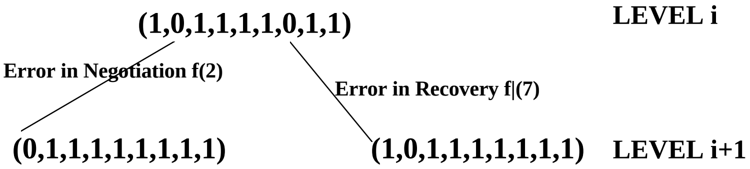


Figure 4.5 Example of two level fault signature

5. ANALYSIS OF THE STEEL MILL COOLING PROBLEM

5.1 Problem Description

The problem of holonic controlled cooling of steel rod has been considered elsewhere[10,11]and is not a main feature of this paper. The aim of this section is to illustrate the manner in which the frameworks for control and diagnosis can be incorporated in this problem. Figure 5.1 illustrates a typical rod rolling mill, where the water-spray cooling zone is

---

[iii] The model described for holonic diagnosis here has been examined in considerable detail in a previous paper [11] .

divided into five cooling boxes each equipped with separate water flow controls. The key goal is to set and control cooling flows so that a desired finish temperature $T_{C\ (\mathrm{FINISH})}$ is achieved, while an additional goal is the minimisation of the surface - to - centre temperature difference during cooling. Both goals are important for the final metallurgical properties of the rod. The current mill system provides only rudimentary control which is susceptible to gradual nozzle blockages and water box failure and is unable to maintain a metallurgical guarantee of properties under these circumstances.

Briefly, the problems and goals proposed in this study were:

PROBLEMS	**GOALS**
System unable to handle new products	Integrate metallurgical based cooling models
Rigidity of cooling set-up	Demonstrate negotiation for set-up (Co-operation)
High maintenance of water boxes	Develop self-diagnosis strategy (Autonomy)

It is noted that each goal in itself does not constitute the requirement for a holonic solution, but the combination of these problems lent itself to analysis within a holonic framework. It should also be noted that the aim of the study was not to improve performance of the system under normal operations but to extend its ability to operate effectively under abnormal or changing conditions.

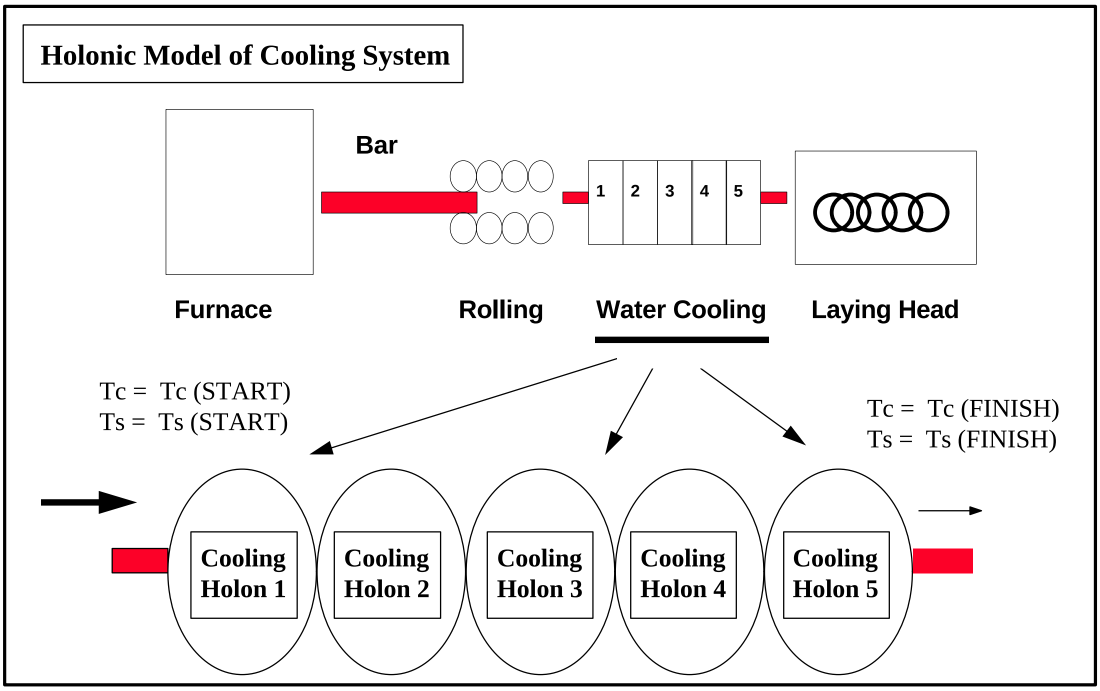


Figure 5.1 Rod Mill Layout and Cooling Holon Diagram

5.2 Holonic Solution

The holonic structure (refer to Figure 3.2) proposed for the cooling problem, comprised three levels of physical process functions:

- ROD MILL LEVEL - unit(s) - one unit per processing path - responsible for setting and achieving goals relating to final product characteristics and meeting production requirements
- COOLING LEVEL - responsible for converting metallurgical goals into cooling sub goals and negotiating optimal approach
- VALVE LEVEL - responsible for water supplies as required (primitive unit)

additionally, a further unit which will interact at different levels is

- MAINTENANCE - human and interfacing functions which interact as required with cooling and valve functions

5.2.1 Set Up/ Control Solution

Each cooling box along with it is control and set-up functions (in a PLC) and its maintenance and repair functions (human operator) represents a holon (refer to Figure 5.1). This allocation is due to the problems encountered in achieving reliable and effective cooling over a range of products and the need for flexibility in the case of failure and/or degradation of a single cooling box. In [10] it is demonstrated that by using a Contract Bidding algorithm a simple and effective co-operation for determining appropriate flows in each cooling box can be obtained. Importantly, the decision making is completed in terms of sub-goals of the overall goals at the local holon level, with the bidding system allowing the holons to negotiation the best solution of these sub goals in order to achieve a consistent solution to the overall goal. A full set of results for this co-operation problem is recorded elsewhere [10]. This process can be written in a hierarchical goal-seeking framework is illustrated in Figure 5.2. The diagram in Figure 5.2 represents an example of an *N-Person, Co-operative Game* [9], where we note that in the case of the holon-based cooling problem, the global decision function is in fact replicated in each of the participating holons in order to ensure smooth operations in the case of a single holon failure.

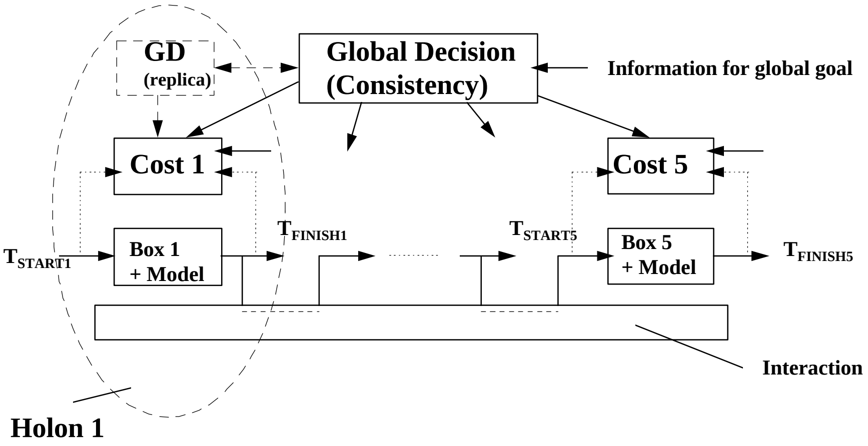


Figure 5..2 Cooling control problem as a Hierarchical Goal Seeking System

The attractive feature of this problem representation is that it is completely generic and the associated analysis and synthesis techniques could equally be applied to the interaction between units in a discrete manufacturing problem such as resource allocation in a machine tooling environment. Further research in this area is required to develop a systematic framework for holonic operation, and particularly the issue of handling multiple sub-holon layers has not been addressed.

5.2.2 Diagnostic Solution

The methodology for handling holonic diagnosis for the cooling problem has only been developed as a conceptual exercise to date. However, this exercise is sufficient to illustrate the mechanics of the holonic diagnosis methodology developed in Section 4.2.

The exercise identified the three most important fault types that occur in the cooling zone. These are (i) the sticking of the spray level control valve which regulates the flow setting (ii) the diverter valve which directs the water flow onto and away from the bar as required sticks (on or off) and (iii) wearing of the internal surface of the spray nozzles which leads to gradual deterioration of flow and cooling quality. It is noted that, in the interests of quality, an operator is currently employed full time to maintain the cooling boxes.

For a full illustration of how the holonic diagnosis of Section 4.2 works the reader is referred to a further paper on this subject[11] However, if simply consider the case of the control valve sticking, Figure 5.3 shows the fault map developed for this particular fault. This demonstrates that there are at least three other fault mechanisms which can be triggered by the same detection (error) signal. Clearly at a local cooling holon level this creates some ambiguity. It can be shown that this detection problem requires a two level fault signature and some external co-operation between cooling holons.

FAULT	INDICATOR	HOLON LOCATION	ERROR	OTHER CANDIDATE FAULTS
Control Valve sticks	SLOW TREND OVER, SAY, 0.5HR	STATE MAP & HISTORY (Database holon)	CONSISTENT TEMP ERROR; POSSIBLY IN WRONG DIRECTION	1. NOZZLE WEAR 2. LEAKING HOSE &/OR CLAMPS 3. REDUCED WATER PRESSURE

Figure 5.3 Section of Fault Map for Cooling Process

6. ACKNOWLEDGEMENTS

The author would like to thank BHP Co. Ltd for their support of this work while he was at BHP Melbourne Research Laboratories.

7. REFERENCES:

1 Morton, A, Manufacturing Technology - On the Cutting Edge, The Economist, March, 1994

2 Bussmann, A Multi Agent Approach for Dynamic Adaptive Scheduling of Material Flow, Proceedings of MAAMAN - 94, Octense, Denmark, 1994

3 Szcerbicki, E., Acquisition of Knowledge for Autonomous Co-operating Agents, IEEE Transactions of Systems, Man & Cybernetics, v23, n5, 1993

4 Tannenbaum, A, Distributed Operating Systems, Prentice Hall, 1994

5 Smith, R., The Contact Net Protocol: High Level Communication and Control in a Distributed Problem Solver, IEEE Transactions on Computing, v C-29, n12, 1980

6 Betlem, B, van Aygele, R, An Object Oriented framework for Production Control, Proceedings of Control 94, UK, 1994

7 Isermann, R, Process Fault Detection Based on Modeling and Estimation Methods - A Survey, Automatica, v20, n4, 1984

8 Patton, R, Frank, P, Clark, R (eds), Fault Diagnosis in Dynamic systems, Prentice Hall, NK, 1989

9 Mesarovic, M, Takahara, Y, Abstract Systems Theory, in Lecture Notes in Control and Information Science, No 116, eds. M Thoma & A Wyner, 1989

10 Agre, J, Elsley, G, McFarlane, D, Cheng, J, Gunn, B, Holonic Control of Cooling Control System, in Proceedings of Rensslaers Manufacturing Conference, New York, October, 1994

11 McFarlane, D, Marett, B, Elsley, G, Jarvis, D, Wilbers, P., Application of Holonic Methodologies to Problem Diagnosis in a Steel Rod Mill , submitted to IEEE Conference on Systems, Man and Cybernetics, Vancouver, October, 1995

12 Rembold, U, et al, Computer Integrated Manufacturing and Engineering, Addison - Wesley, 1993

13 Rehg, J., Computer Integrated Manufacturing, Prentice Hall, 1994

14 Koenig, D, Computer Integrated Manufacturing- Theory and Practice, Hemisphere, 1990

15 Scheer, A-W, CIM - Towards the factory of the future, Springer Verlag, 1988 (revised 1991)

16 Proceedings of the 1st European Conference on Holonic Manufacturing Systems, Hannover, December, 1994

17 Koestler, A., The Ghost in the Machine, (1st Published) Hutchinson & Co, London, 1967

18 Christensen, J., Holonic Manufacturing Systems - Initial Architecture and Standards Directions, in Proceedings of the 1st European Conference on Holonic Manufacturing Systems, Hannover, December, 1994

19 Jamshidi, M, Large Scale Systems - Modelling and Control, North Holland Series in Systems Science and Engineering, The Netherlands, 1983

20 Singh, M, Decentralised Control, North Holland Series in Systems Science and Engineering, The Netherlands, 1981

21 Basseville, M., Nikiforov, I., Detection of Abrupt Changes, Prentice Hall, 1993

22 Warneke, H, The fractal enterprise, Springer - Verlag, 1993

23 Van Brussel, H, Holonic Manufacturing Systems - The vision matching the problem, in Proceedings of the 1st European Conference on Holonic Manufacturing Systems, Hannover, December, 1994

24 Green, D, Limebeer, D, Linear Robust Control, Prentice Hall, 1994