30

DESIGN ISSUES IN HOLONIC INVENTORY MANAGEMENT AND MATERIAL HANDLING SYSTEMS

Martyn Fletcher
Agent Oriented Software Ltd, Mill Lane,Cambridge, CB2 1RX, United Kingdom,
martyn.fletcher@agent-software.co.uk

Vladimír Mařík
Department of Cybernetics, Czech Technical University in Prague, Czech Republic &
Rockwell Automation Research Center, Americka 22, 120 00 Prague, Czech Republic,
marik@labe.felk.cvut.cz

Pavel Vrba
Rockwell Automation Research Center, Americka 22, 120 00 Prague, Czech Republic
pvrba@ra.rockwell.com

Holonic manufacturing systems (HMS) represent a novel paradigm for addressing the problems encountered by 21st Century engineering businesses. These next generations of decentralised AI-based shop-floor control systems are geared towards: (i) high-variety low-volume manufacturing, (ii) placing these customer-specific products into the market with short order-to-delivery times, and (iii) providing a fast return on investment. The paper presents a model of a Holonic Inventory Management System (HIMS) linked with an agent-based material handling within an agile manufacturing environment.

1. INTRODUCTION

Holonic manufacturing systems (HMS) represent a novel paradigm to address some critical problems faced by manufacturing businesses as they come to grips with the 21st Century market. Yet, the application of HMS principles places a severe strain on how inventories of raw materials, work-in-progress and finished goods are to be managed within the frame of a vision of a holonic factory. This is particularly so when there is demand for mass customization. This topic has not received much attention in the HMS community, but it needs addressing if businesses are to buy into the holonic vision and deploy holonic technologies in their factories.

Centralized solutions to controlling inventory, within the scope of such agile environments, do not work since they are slow to react, impose operational bottlenecks and are a critical point of failure. Holonics is a decentralized 'bottom up' approach and provides principles to ensure a higher echelon of responsiveness and handling of system complexity. The fundamental building blocks of a HMS are

V. Mařík et al. (eds.), *Knowledge and Technology Integration in Production and Services*

called *holons* to reflect the fact that these entities: (i) are both parts and wholes (Koestler, 1967), and (ii) behave simultaneously in an autonomous and cooperative fashion (Suda, 1989). Holonics is not just a new technology, but rather it is a system-wide philosophy for developing, configuring, running and managing the next generation of manufacturing business where flexibility is the paramount (Marik, *et al.*, 2002). Here we focus on the flexibility needed by the inventory management system inside a HMS and how holons can support these requirements. We propose that a holonic inventory management system (HIMS) can be characterized by several types of newly introduced holons:

- *Pick-and-Place robot holons* will distribute picking and placing tasks evenly amongst themselves, will select optimal routes to navigate along and will load different types of goods into the same collection bin attached to the robot (e.g. with the heaviest items at the bottom).
- Each item of stock being regarded as an independent *workpiece holon*. Thus it can play an active and intelligent role in getting itself manufactured on time, stored in the correct manner and so forth.
- *Shelf holons* will advertise how best their storage services can be used.

We also assume that there are the necessary *resource holons* to provide transformation, transportation and validation services (Van Brussel, *et al.*, 1999), as well as *order/product holons* to represent orders into the factory and provide knowledge on how these orders can be processed (Wang, 2001) (Xu, *et al.*, 1999). We get such holonic inventory management systems to work in the real world through investigating a number of design issues. The context for this pragmatic investigation is that a physical environment is provided by a variety of factories with different attributes. For example, the multi-cell holonic demonstrator (Chirn and McFarlane, 2000) being developed at the University of Cambridge's Institute for Manufacturing provides a machining and assembly environment. Meanwhile the lumber mill scenario of (Kotak, *et al.*, 2001) requires flexible storage for wood products during disassembly. Furthermore the automobile scenario of (Bussmann and Sieverding, 2001) has an agile engine assembly line where partially-complete engines must be stored while rush orders move through the line, or while assembly and inspection stations are busy/broken. Each of these, and other HMS test case environments need inventory management to varying extents. What is more, these physical environments are to be controlled using distributed artificial intelligence and so need a holonic solution to inventory management and material handling.

2. DESIGN CHALLENGES FOR A HOLONIC INVENTORY MANAGEMENT SYSTEM

A Holonic Inventory Management System (HIMS) is going to play a critical role in the next generation of holonic manufacturing systems because all of these systems demand flexibility to hold finished goods, work-in-progress (WIP), raw materials and any hybrid mixture in a unified fashion. Owing to space limitations in factories and the cost of installing the dedicated warehousing, an agile model for storing and retrieving goods is essential for smoothing out any peaks and troughs in demand.

This is especially so when dealing with assembly because some sub-ordinate workpieces must be held in the warehouse until all the constituent parts are available ready for aggregation. When the foundation for modelling, the decentralised control system needed to manage this warehouse is intelligent software agent-based holons then the solution is a HIMS. The key facets of a HIMS are illustrated in Figure 1.

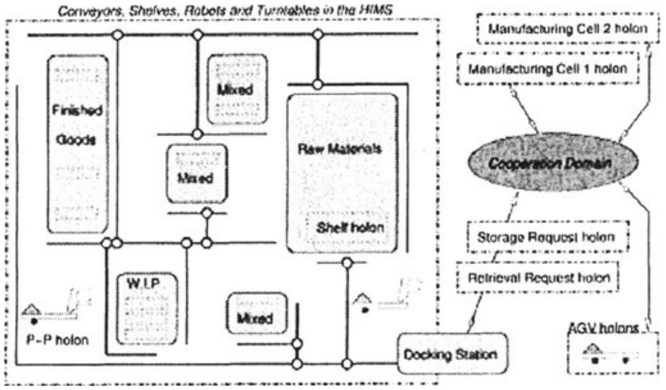

Figure 1 – Scope of a Holonic Inventory Management System

As can be seen in Figure 1, the HIMS interacts with the various manufacturing cell holons and groups of Automated Guided Vehicle (AGV) holons in order to collect, store, retrieve and deliver necessary inventory in a timely manner. These interactions take the form of structured negotiations and take place through a logical structure known in the HMS terminology as a *cooperation domain.* The gateway between the HIMS and the rest of the factory is one or more docking stations, at which AGVs may load and unload physical inventory.

The creation of a sequence of steps in which AGVs dispose of and collect goods is a classic scheduling problem. Therefore it is NP-hard when there are more than one AGV or when there are more than one docking station. This is another reason for adopting a holonic solution to the load/unload problem as holons have the facilities to deliberate, cooperate and act proactively in order to determine a feasible, if not optimal, strategy for sequencing and timing the arrival/departure of such AGVs. Within the confines of the HIMS, Pick-and-Place (P-P) robots move around the warehouse environment to: (i) transport recently-received inventory from the docking station and put it onto shelves; and (ii) take requested goods off the appropriate shelves and transfer them to the docking station for subsequent collection by an AGV. There are several routes that a Pick-and-Place robot can take from the docking station(s) to the appropriate shelf, and vice versa. Furthermore, the robot can collect and place several pieces of inventory on a single tour around the warehouse. For example it may visit shelf s12 to collect workpiece w4, then collect w8 from s32, deposit w90 onto s54, and then return to one of the docking stations. Hence we have a travelling salesman problem where the robot must visit a set of shelves and try to establish the least cost routes between subsequent shelves in order to minimise the overall journey time. Moreover, as conveyors break down, stock is moved by human personnel (also working in the warehouse environment) and the journey times between any two shelves may change over time.

Our solution is based on automatic identification (AutoID) technology (http://www.autoid.org) where an independent agent represents each workpiece and each shelf is a holon equipped with a tag reader. Each of the Pick-and-Place robots has four degrees of freedom: up/down, left/right, in/out of shelves, and between independent shelves within the WIP, mixed, finished goods or raw materials areas (see Figure 2). When gathering goods, these robots select one physical workpiece at a time and deposit it into their collection bins while ensuring that the biggest or heaviest items are loaded at the bottom of the bin and lighter/smaller items at the top. When depositing items into the shelves, the robot (in conjunction with other holons) selects the optimal slot into which the workpiece can be inserted, based on some heuristic algorithm with a view towards achieving global coherence.

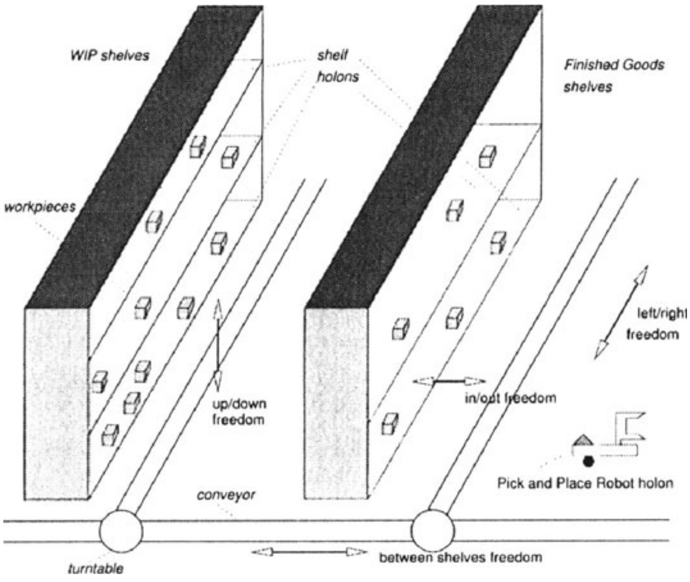

Figure 2 – Degrees of Freedom for the Pick-and-Place Robot Holons

A fundamental design issue in such a HIMS (with its associated decentralised control) is how to ensure global coherence when individual agent-based holons are acting to maximise their own, possibly mutually conflicting, goals. In the context of this mini-factory, coherence can be viewed as minimising any disadvantages of distribution, and would be measured in terms of performance. In other words, a coherent HIMS is one that behaves (from an external viewpoint) with a performance equal to that displayed by a centralised system capable of performing all the inventory management tasks needed. Hence the integration of *pathfinder holons* to act as expert systems on planning the travelling salesman circuit can contribute to such coherence (Jarvis, *et al.*, 2001). Moreover, they can be easily incorporated within the architecture proposed for the physical holonic demonstrators since the routes and item picking/placing sequences offered by these holons are recommendations that the Pick-and-Place robot holons can either accept or reject.

In this bottom-up or emerging behaviour approach, no central controller exists and the individual holons (with the aid of their agent-based decision-making software) act in an autonomous fashion in such a way that the behaviour of the entire HIMS emerges. This approach is similar to the way in which ant colonies operate with many (say 10,000) ants each searching for food in their environment.

There is no global commander (not even the queen ant) and every ant has very limited intelligence, in fact their can only obey a limited set of simple rules and communicate with each other using pheromones. Yet, from a global perspective, they appear to operate in both unison and smartly. The key problem with this purely bottom-up approach is that the behaviour that the ants, or the Pick-and-Place robot holons, workpiece holons, shelf holons and so forth in our HIMS, will produce cannot be predicted prior to execution, and neither can it be controlled in a top-down manner during execution, as there is only a limited hierarchical command structure. Therefore a compromise is demanded. Our solution is that:

- *A pathfinder holon* is put in charge of ensuring that the circuit that the robot will travel is as close to optimal as possible.
- The responsibility for ensuring all the workpiece insertions and removals required to store the factory's stock are handled by the corresponding *storage request holon* and *retrieval request holon.*
- Actual movement of physical items is governed in a distributed manner between the one or more Pick-and-Place holons, the workpiece holon, the multiple shelf holons and the product holon.

Therefore a *holarchy* is generated to best assign work amongst the holons of a particular class (e.g. allocating a storage job among the candidate shelves). This assignment is founded on various agent-based protocols like the classic 4-step contract net protocol, English or Dutch auctions, or market economy approaches.

3. HOLONIC INVENTORY MANAGEMENT SYSTEM

This section addresses one of the critical design issues for realising a holonic inventory management system regarding the storage and retrieval of workpieces. Decisions on where and when workpieces are to be stored/retrieved from the shelves is under the joint control of several distributed holons in the form of a *holarchy.* The holon types involved in the negotiations include: the retrieval/storage request holon, the Pick-and-Place robot holon, the workpiece holon, the team of resource holons (each representing an independent shelf), the pathfinder holon to help in selecting the optimal route the robot should take, and the product holon with its knowledge on how workpieces should be held in the warehouse. Cooperation domains are used to aid the holons in their negotiations. These concepts are illustrated in Figure 3. To insert an item into the HIMS (a storage request), the subsequent protocol is used:

1. The manufacturing cell holon that needs to store a workpiece w1 issues a request to the cooperation domain (see Figure 1). This request fully specifies what w1's characteristics are, how w1 is to be retained on the shelves, and what is its expected times of arrival/departure to/from the HIMS.
2. A new storage request holon is created to manage the transfer of the item and its subsequent storage. The storage request holon acts as an interface between the main holonic factory and the HIMS.
3. The storage request holon creates a new cooperation domain to orchestrate these management activities (see Figure 3) and so a new holarchy of HIMS holons will be generated.

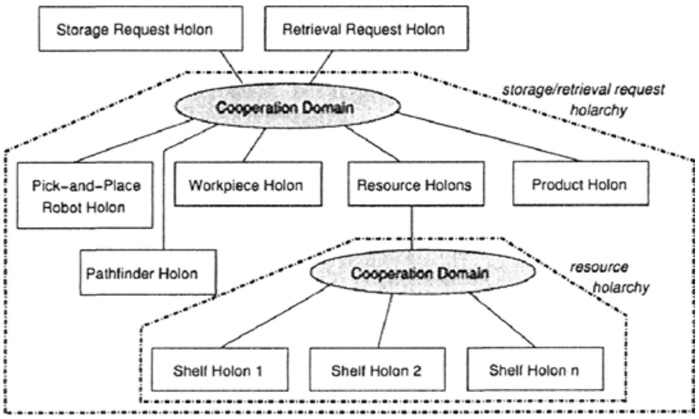

Figure 3 – Creating a Holarchy for a Storage or Retrieval Request.

4. A storage request is issued into the cooperation domain (where all of the available HIMS holons can receive information). This request contains the specification data provided by step 1.
5. A suitable product holon, of the same class as the workpiece being stored, joins the cooperation domain and provides knowledge about the types of shelves that can hold the workpiece.
6. The available shelf holons respond to the request indicating whether the workpiece can be stored (while satisfying the specified retention criteria given by the product holon) and what time it should be delivered to the docking station. They also inform the workpiece holon of how it is to be stored.
7. The storage request holon is told how much 'electronic money' that this storage will cost to hold the workpiece holon for the specified duration.
8. A resource holarchy is generated to find the appropriate shelf where the workpiece can be held. A market economy is used to support this pricing and to get the suitable shelf holons (sellers) to offer their storage capacity to the storage requester holon (acting as buyer) so that the workpiece will be assigned to the shelf holon offering retention at the lowest cost.
9. If the manufacturing cell holon and the storage request holon find this proposal satisfactory then a classic contract net protocol is established to get the workpiece to the docking station:
    a. A subsequent cooperation domain is created in order to arrange for an AGV to transport the said item to the docking station for arrival at the prescribed time.
    b. The storage requester holon invites bids from the AGV holons to perform the transport.
    c. AGV holons respond giving their bids in terms of collection time, availability and cost.
    d. The storage requester holon selects the best bid and awards a contract to the selected AGV.
10. The transport from the docking station to the correct shelf via a Pick-and-Place robot holon also must be arranged. Optimally, the workpiece should be

unloaded onto the docking station and loaded onto the robot with a minimal delay (i.e. the workpiece holon's objective) while balancing against the robot's objective (not being idle at the docking station waiting for the item to arrive).

11. The circuit around the shelves that the robot will adopt is created by the pathfinder holon based on the requests for storing and retrieving items, together with the times and sizes of these items. The robot will put larger heavier items at the bottom of its bin. The knowledge about how to perform such stacking is provided by the product holon. This problem is complex and is made even more complicated by the changes in workpiece delivery schedules and so forth.
12. When the workpiece arrives at the docking station, the attached AutoID tag is read and the physical item is either loaded into the waiting Pick-and-Place robot' collection bin, or is held at the docking station for a limited period until the robot arrives.
13. The robot then moves through its route so that it arrives at the assigned shelf with the workpiece easily available from its collection bin (i.e. at the top or close to it). The robot then takes the item out and places it onto the shelf.
14. As the physical workpiece is entering the shelf, the reader attached to the shelf reads the tag for the item's number. The shelf holon confirms that this item should be stored here and informs the workpiece holon, through the connected factory (wireless) network, that the corresponding physical item has been successfully deposited.
15. This concludes the storage activity and so the various holarchies, cooperation domains as well as the storage request holon are destroyed.

To remove an item from the HIMS (i.e. a retrieval request), a similar protocol is used. Yet in this case, a retrieval request holon is in charge of acquiring the desired workpiece from the shelves. Therefore a cooperation domain is established by either: (i) the workpiece holon (if it knows its deadline for being manufactured is quickly approaching); or (ii) by the manufacturing cell holon (if it will require the workpiece, say for assembly with another item, at some time in the near future).

4. AGENT-BASED MATERIAL HANDLING SYSTEM

This section provides a brief description of the ideas behind the multi-agent material handling system developed at the Rockwell Automation Research Center Prague. The attention is paid mainly to the transportation of workpieces among different manufacturing cells using AGVs. The first design of the agent-based FIPA (Foundation for Physical Intelligent Agents) compliant solution of the material handling problem, namely of the transportation of workpieces through the factory using conveyor belts can be found in (Vrba, Hrdonka, 2001). The basic material handling components such as a work-cell, conveyor belt, diverter/intersection and workpiece were identified and appropriate FIPA-compliant agents were developed. The behaviour of these agents was aimed at solving the discrete transportation task, i.e. the delivery of a particular workpiece from the source to the destination work-cell using conveyors. To accomplish such behaviour, the FIPA-compliant messages for inter-agent communication as well as an appropriate knowledge ontology providing agents with relevant semantics of messages were proposed.

The main stress was put on the dynamic reconfiguration capabilities, i.e. to be able to safely react to the failures of components. We call it *light-weight* reconfiguration – if a holon detects a failure of its physical device (e.g. conveyor stops for some reason), it sends a message to the other agents that a failure has happened. They update their routing knowledge and find other optimal routes throughout the factory avoiding the broken component. A kind of *heavy-weight* reconfiguration was considered as well to allow the physical restructuring of the system. It includes the removal of any component from and/or the integration of new components into the system at runtime without the need to stop the system. To demonstrate the functionality of this solution and to show the benefits of the agent technology in particular, the simulation tool was developed in the JAVA language using two open-source agent development toolkits, FIPA-OS and JADE.

Recently, the proposed multi-agent solution was extended to integrate another transport component – the AGV. As shown in Figure 4 we suggest that the AGVs follow a network of tracks (we call it *AGV path*) located on the factory's floor (a very usual approach used today). The AGV path comprises of the so-called *AGV sections* connecting *AGV nodes*, where a node can be either the *work-cell*, or the *junction* (a node where two or more AGV sections are joint) or a simple *curve*.

Unlike diverters or conveyor belts, the specification of the AGV agent and its behaviour seems to be much more complex task. The AGV must be able to find shortest routes through the AGV path, must be able to negotiate with the work-cells about the delivery and be capable of avoiding collisions with other AGVs. To accomplish all of these requirements we decided to equip the AGV with the complex knowledge about its environment.

First, the AGV is provided with the precise knowledge (ontology) regarding the AGV path it follows. When the AGV agent is created it is given the XML description of the path specifying where the AGV nodes are located (x, y coordinates), what is their type (work-cell, junction, curve) and how these nodes are interconnected via the AGV sections. The AGV translates this description into an appropriate object model and consequently performs a searching algorithm to find all the possible routes to work-cells from each junction node. A *home section* is specified for each AGV – when the AGV has completed the delivery task and/or it has currently nothing to do, it returns to its home section and waits there idle. When integrated with a HIMS, the home section might be an appropriate docking station.

Second, while the AGV moves it has to be aware of other AGVs to predict and avoid possible collisions. On one hand, a collision in the area around a junction node can occur as two or more AGVs try to enter it simultaneously (each of it from different section). On the other hand there can be a collision called *head-to-head deadlock* when the AGV wants to enter some section in a particular junction, but there already is another AGV moving in this section heading to the same junction

To solve the former type of collision, we had to introduce a special agent for each junction node responsible for the scheduling of the AGVs' movement in the area around the junction. When some AGV is about to enter such an area it sends a message to the *junction agent* asking whether the area is free or not. If the area is free, the node agent gives the AGV a permission to enter the node whilst locking the area for this AGV for appropriate time period (after this period the lock is automatically released). No other AGVs are allowed to enter the junction within this period – they have to wait until the area is made free.

Solving head-to-head deadlocks is an even more complicated issue. When the AGV approaches a junction node it chooses one of the sections connected to this junction which should be used next to get to the AGV's intended destination. But a collision can happen in this section if there already is another AGV moving in the opposite direction. To predict such a situation the AGV should know in advance, if the section is free or not. To accomplish it, two different approaches can be used. Each AGV holds the information about where all the other AGVs currently are (and in which directions they move). This information is updated via messages sent by each AGV to all others when it leaves a section for another one. The disadvantage of this approach we are using now could be a huge amount of messages with the increasing number of AGVs. To reduce the communication traffic we plan to extend the abilities of the junction agents by applying the 3bA acquaintance models for organising and maintaining social knowledge (Marik, *et al.*, 2001).

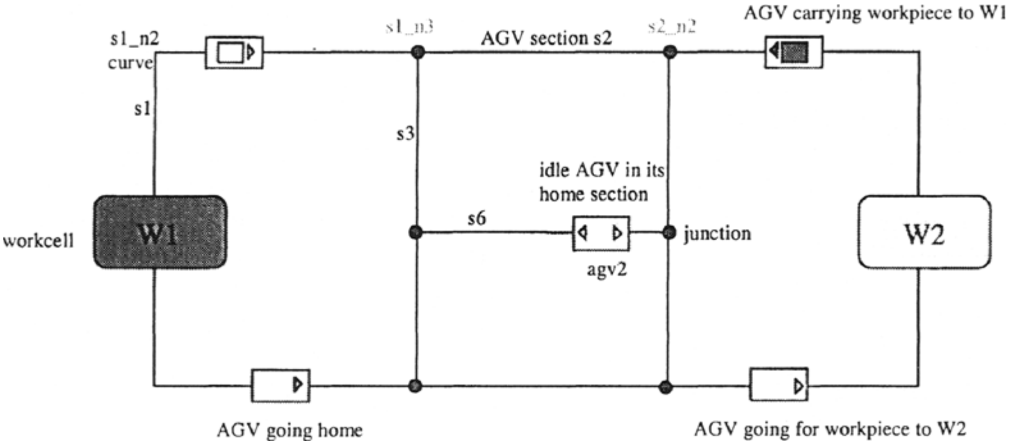

Figure 4 – Material handling using AGVs.

If there is a colliding AGV (lets say A2) in the section where A1 wants to continue, A1 sends a <deadlock?> message to A2. If A2 plans to continue towards the section, occupied by A1, it replies <deadlock!> saying that there is a head-to-head deadlock, otherwise replies with <noDeadlock>. In both these cases, A2 adds an estimate of the time period in which it will take to reach the junction node. A1 then decides, whether it is better to choose another section with respect to the time period it will have to wait until the colliding AGV reaches the junction. If it decides to wait and there is really a deadlock, the AGV moves to another (third) section (if available) where it stops and waits until A2 enters the freed section.

According to ideas presented in §3 for the workpiece delivery purposes the contract-net-protocol negotiation is used (see step 9 of the protocol mentioned in the section 3). Let us note, that the behaviour of pick-and-place robots can be easily described using the same patterns as in the case of AGVs presented in this section. Each group of shelves depicted in Figure 2 can be treated as a single source or destination work-cell. The only extension needed is to define a communication scenario determining which shelf (i.e. additional *up-down* movement) and what position on this shelf (*left-right* movement) that must be reached in order to store/retrieve the workpiece correctly.

5. CONCLUSIONS

The paper presents a new (holonic) approach to inventory management as an extension of the holonic visions into the area, which is usually out of the main stream of attention of the holonic research. Here each item of inventory, every shelf and every Pick-and-Place robot is treated as a holon. The other decentralised holons (i.e. the pathfinder holons, storage request and retrieval request holons) considered here are rather software (information) agents as they are not directly connected with any physical transportation/storage hardware. They are expected to "live" just temporarily, for the period needed to accomplish the given storage/retrieval mission.

Overall the proposed approach works well with a high degree of agility (especially with respect to stock movement planning) and is more reactive to environmental changes than existing approaches. Future work will focus on the implementation of this HIMS model with each holon modelled as an autonomous agent, and holon actions/interactions represented using well-established *belief-desire-intention* and *coalition-formation* ideas. Moreover we intend to deploy our generic model into a physical environments and conduct experiments to prove our hypothesis that holonic inventory management is needed to support the flexibility required by 21st Century manufacturing businesses.

6. REFERENCES

1. Bussmann S, Sieverding J. Holonic Control of an Engine Assembly Plant: An Industrial Evaluation. In Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 2001.
2. Chirn JL, McFarlane DC. Building Holonic Systems in Today's Factories: A Migration Strategy. . Journal of Applied System Studies, special issue on Holonic and Multi-Agent Systems, 2(1), 2000.
3. Jarvis D, Jarvis J, Lucas A, Ronnquist R, McFarlane DC. Implementing a Multi-Agent Systems Approach to Collaborative Autonomous Manufacturing Operations. In Proceedings of IEEE International Conference on Systems, Man and Cybernetics, 2001.
4. Koestler A. The Ghost in the Machine. Arkana, 1967.
5. Kotak DB, Fleetwood M, Tamoto H, Gruver WA. Operational Scheduling for Rough Mills Using a Virtual Manufacturing Environment. In Proceedings of IEEE Int. Conf. on SMC, 2001.
6. Marik V., Fletcher M., Pechoucek M.: Holons & Agents: Recent Developments and Mutual Impacts. In: Multi-Agent Systems and Applications II. LNAI No. 2322, Springer Verlag, Heidelberg, 2002
7. Marik V, Stepankova O, Pechoucek M. Social Knowledge in Multi-Agent Systems. *Multi-Agent Systems and Applications.* LNAI No. 2086, Springer Verlag, 2001
8. Suda H. Future Factory System. In Japan. Journ. of Advanced Automation Technology, vol. 1, 1989.
9. Van Brussel H, Bongaerts L, Wyns J, Valckenaers P, Van Ginderachter T. A Conceptual Framework for Holonic Manufacturing: Identification of Manufacturing Holons. Journal of Manufacturing Systems, **18**(1), 1999.
10. Vrba P, Hrdonka V. Material Handling Problem: FIPA Compliant Agent Implementation. In Proceedings of the Twelfth International Workshop on Distributed and Expert Systems Applications DEXA, 635-639, 2001.
11. Wang L. Integrated Design-to-Control Approach for Holonic Manufacturing Systems. Journal of Robotics and Computer Integrated Manufacturing, vol. 17, 2001.
12. Xu Y, Brennan RW, Zhang X, Norrie DH. A Genetic Algorithm-based Approach to Holon Virtual Clustering. Technical report of the Mechanical and Manufacturing Engineering Department, University of Calgary, Canada, 1999.