The holonic enterprise: a model for Internet-enabled global manufacturing supply chain and workflow management

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Abstract
Merges the latest results obtained by the holonic manufacturing systems (HMS) consortium with the latest developed standards for platform interoperability released by the Foundation for Intelligent Physical Agents (FIPA) to propose a novel e-business model: the holonic e-enterprise (HE). The HE extends both the HMS and FIPA models. On one side it extends the holonic manufacturing paradigm with one top level, the inter-enterprise one. On the other side it extends the multi-agent system (MAS) paradigm to the hardware (physical machine) level.

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Introduction

In the context of today's tremendous advances in information and networking technologies the World Wide Web (WWW) is enabling partnerships otherwise impossible in all areas of our life. The static, centralized, sequential, closed, over-the-wall models of the exclusively-competitive world are one-by-one replaced by dynamic distributed, parallel, open collaborative strategies calling for new organizational paradigms supporting globalization of all aspects of life (McHugh *et al.*, 1995). The race for success in the connected world is governed by the way enterprises are able to use the power of the novel information infrastructures that support dynamic clustering and service deployment in an open environment (Agentcities, 2002). Latest advances in distributed artificial intelligence have enabled software emulation of real-life communities as multi-agent systems (MAS). By cloning real-life entities (people, machines and organizations) as software agents connected via the Internet, a virtual society emerges in Cyberspace and the WWW becomes a dynamic environment through which agents move from place to place to deliver their services and eventually to compose them with the ones of other agents, just like people cooperate by exchanging services and/or putting together their competencies in a larger, more complex service.

Thus the WWW is today a dynamic service environment (DSE) information infrastructure that supports production and binds organizations together in the networked economy. In particular, production processes are information rich and the dynamics of the information infrastructure is the tool for carrying it out both at individual locales and across the global environment. The electronic linking implies that work matter (or critical parts of it) is being transferred across virtual locales via the DSE, which supports organizational information that, in turn, can mirror social organization.

The Holonic Enterprise (HE) has emerged as a business paradigm from the need for flexible open reconfigurable models able to emulate the market dynamics in the networked economy (McHugh *et al.*, 1995), which necessitates that strategies and relationships evolve over time, changing with the dynamic business environment.

We begin with an overview of the three main concepts used to develop our HE model: holonic systems, MAS, and the Internet. Next, the role that mediator agents play in holonic systems is described, along with various patterns of holonic collaboration. This leads to the description of the HE model and, finally, an illustrative example of how this model can be applied to a typical manufacturing enterprise.

Background

The holonic systems paradigm

The main idea of the HE model stems from the work of Koestler (1967). In his attempt to create a model for self-organization in biological systems, Koestler has identified structural patterns – namely that they form nested hierarchies of self-replicating structures, named holarchies. Koestler proposed the term "holon" to describe the elements of these systems. This term is a combination of the Greek word *holos*, meaning "whole", with the suffix *-on* meaning "part", as in prot*on* or neur*on*. This term reflects the tendencies of holons to act

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as autonomous entities, yet cooperating to form apparently self-organizing hierarchies of subsystems, such as the cell/tissue/organ/system hierarchy in biology (Christensen, 1994). Holons at several levels of resolution in the holarchy behave as autonomous wholes and yet as cooperative parts for achieving the goal of the holarchy. Within a holarchy, holons can belong to different clusters simultaneously, displaying rule-governed behavior. The rules define a system as a holon with an individuality of its own; they determine its invariant properties, its structural configuration and functional pattern. The duality autonomy-cooperation as main contradictory forces within a holarchy is balanced by the rules that define the functionality of such a system of semi-autonomous holons.

From a software engineering perspective, a holon, as a unit of composition retaining characteristic attributes of the whole system (holarchy), can be viewed as a class. Thus the object-oriented paradigm seemed suitable for modeling holarchies as software systems (Booch, 1994).

The multi-agent systems paradigm

In response to the need for modeling the complexity of interactions in large-scale distributed systems, agent technology has emerged as a paradigm for structuring, designing and building software systems that require complex interactions between autonomous distributed (software) components. While the object-oriented paradigm models systems focusing on the structural, static characteristics of their parts, which are defined through encapsulation and inheritance, the agent paradigm models systems focuses on the underlining dynamics defined by the interactions between their parts. In contrast to the passive way in which objects communicate by invoking methods in one another in a way controlled externally by the user (e.g. from a "main" program), agents are capable of initiating communication and deciding (like a human) when and how to respond to external stimuli (e.g. manifested on them as requests from other agents). From this perspective the agent paradigm extends the object paradigm in that agents can be regarded as proactive objects (Wooldridge, 2001) that have an internal mechanism which governs their behavior, enabling them to initiate action as well as respond to the outside environment in an autonomous way. With this in mind one can define:

- an intelligent agent as a software entity which exhibits, in some significant measure, autonomy, intelligence, and environmental awareness, and which interacts with its environment to achieve internal goals;
- a MAS as a software system in which program modules (the individual agents) are given autonomy and intelligence and an underlining coordination mechanism (implementing rules for collaboration, like for holarchies) which enables collaboration between such modules (agents) to attain system objectives.

A software representation of a holarchy thus appears natural as MAS, consisting of autonomous yet cooperative agents. From this perspective a MAS is regarded as a system of agents (software holons) which can cooperate to achieve a goal or objective. The MAS (software holarchy) defines the basic rules for cooperation of the agents (software holons) and thereby limits their autonomy. In this context, autonomy is defined as the capability of an entity (i.e. agent or holon) to create and control the execution of its own plans and/or strategies, while cooperation is the process whereby a set of entities develop mutually acceptable plans and execute them.

The common denominator between holonics and MAS as paradigms is obviously the focus on the dynamics of the interactions. However, in a MAS there is no pre-assigned condition that the interactions should be driven by cooperative forces, while in a holonic system this is a precondition for the existence of the holarchy *per se* (the glue that binds the holarchy together driving it towards the common goal). It is this "team-spirit" that characterizes a holarchy, in that all its component parts at all levels of resolution work together towards achieving the goal in an optimal manner. This "togetherness" drives the self-organizing power that configures all the sub-holons to optimize the interactions within the holarchy to reach the common goal with maximum efficiency. On the other side, in a MAS, agents may interact based on competitive rather than cooperative rules (e.g. electronic markets or other competitive/conflicting environments such as military scenarios; competing over resources or societal/political disputes, etc.) – which is excluded as a possibility in a holarchy.

The Internet

The MAS paradigm has challenged the software world and with it the world of information technologies through its ability to enable emulation in Cyberspace of real-world societies as virtual communities of agents. The marriage between MAS and the Internet has created a parallel world of

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information that "lives" in the Web universe emulating our games in all aspects of life, be they economic, financial, business, school or health-related, or even just-for-fun in computer games.

MAS enable cloning of real-life systems into autonomous software entities with a "life" of their own in the dynamic information environment offered by today's Cyberspace. The WWW connects by invisible links these entities through their virtual "clones" forming "societies" in which the virtual entities (mostly modeled as software agents) have their own "life" interacting with an autonomy of their own. When such virtual societies are driven towards a common purpose they cluster into collaborative holarchies (Ulieru, 2002).

Enterprises partially "cloned" as agents that interact over the Internet, can cluster as well into holarchies to form global virtual organizations. Two main enterprise-related paradigms have emerged supported by this technological development: the Web-centric enterprise and the virtual enterprise.

Unlike existing point solutions that focus on a single-department or activity product, such as data management or product-design-and-manufacturing, the Web-centric model (Hornberger, 2001) addresses product and process life-cycle management across the extended enterprise regarded as a global organization. At the core of the Web-centric enterprise model is the Internet-enabled software infrastructure acting as a worldwide open DSE. Such an integrated framework enables sharing of information, services and applications among suppliers, employees, partners and customers via:

- Deployment of automated, intelligent software services (e.g. Internet-enabled negotiations, financial transactions, advertising and bidding; order placement/delivery, etc.).
- Complex interactions between such services (e.g. compliance policies; argumentation and persuasion via complex conversation protocols, etc.).
- Dynamic discovery and composition of services to create new compound value added services (e.g. dynamic virtual clustering of synergetic partnerships of collaborative organizations aiming to achieve a common goal).

A virtual organization or company is one whose members are geographically apart, usually working by electronic linking via computers while appearing to others to be a single, unified organization with a real physical location. Within a virtual organization, work cannot be completed without support of an information technology infrastructure in linking the parts.

The virtual enterprise (VE) paradigm differs from the Web-centric paradigm in that a VE is a distinct organizational form, not just a property of any organization. Thus, Web-centric organizations that can use communications extensively, but not in a way critical in fulfilling the goal of the organization (e.g. a multinational corporation with dispersed parts being on the same satellite network whose use, however, is not critical for completing the production process) are not VE. In today's global economy in which enterprises put together their competitive advantage to leverage a higher purpose otherwise impossible to achieve, the VE is an appropriate model for strategic partnerships. Such a strategic partnership model calls for new perspectives on competition in the global open Internet-enabled economy.

The networked economy mandates the shift from industrial age, "brick-and-mortar" strategic thinking to an emphasis on new alliances and a rethinking of traditional partnerships. Alliances and partnerships can be formed in ways that increase value for all players. The concept of co-opetition (Brandenburger and Nalebuff, 1996) builds on the duality inherent in all relationships with respect to win-win and win-lose interactions. The success of most businesses is dependent on the success of others, yet they must compete to capture value created in the market and protect their own interests. The main issues to be addressed when developing a business strategy based on co-opetition are:

- Who are the players in the network and how can they collaborate to maximize value?
- Which relationships are complementary in nature – which companies can add value to what they provide?
- Which players are competitors, and are there mutually beneficial ways to create value?
- What can they do to sustain their competitive advantage over time?

Holonic collaboration

In this section, we discuss how the holonic paradigm supports collaborations of autonomous entities. This results in the basic holonic notion of autonomous and cooperative building blocks (i.e. holons) that are used to lay the foundation of the HE discussed in the next section.

The mediator architecture

A system decomposition and analysis based on holonic principles naturally suggests a distributed software implementation, with autonomously executing cooperative entities as building blocks. As illustrated in Figure 1, the stable intermediate forms/holons of the system can be implemented at the lower levels by objects, at the medium level by agents, and at the higher levels by groups of agents, with these mapping decisions being application-specific. (Of course, these are only the software portions of the holons.) Also, holons should have an interface which is simple and cohesive, just like in object-oriented systems (Eliens, 2000) or any effective organizational structure, and which is itself a holon.

In the previous section we emphasized on the cooperative forces that drive the holons towards achieving the common purpose of the holarchy. How does one build agents and groups of agents which fulfill the holonic philosophy? (The third option, mapping holons into objects, is an almost trivial task that needs no discussion here.) The basic condition for holonic systems is that a holon is simultaneously a "whole" and a "part" of some other whole/holon. This means that holons may contain other lower level holons, and may themselves be contained in other higher level holons, resulting in a recursive architecture. The agents to be used to implement this holonic system will be considered independently executing processes on some computer/machine/device. In this case, if a one-to-one mapping of holon to agent is performed, it is much more difficult to implement an agent practically (than it is to conceptualize a holon) which is itself a component of a higher level agent and which also contains lower level agents.

Here, the concept of a mediator agent comes into play. The mediator will fulfill two main functions. First, it acts as the interface between the agents in the holon and between the agents outside the holon (i.e. acts as a type of facilitator); conceptually, it can be thought of as the agent that represents the holon. Second, it may broker and/or supervise the interactions between the sub-holons of that holon; this also allows the system architect to implement (and later update) a variety of forms of interaction easily and effectively, thereby fulfilling the need for flexibility and reconfigurability. Such a mediator as described can actually be considered a static mediator, and will exist primarily at the boundary of a homogeneous holon (such as an ordering holon in a supply chain example), as illustrated in Figure 2.

In manufacturing holarchies the mediator encapsulates the mechanism that clusters the holons into collaborative groups (Maturana and Norrie, 1996).

This type of mediator is a "dynamic mediator". In the case of interactions between heterogeneous holons, such as an order holon and various resource scheduling holons, ease of system design may be supported by employing a dynamic mediator agent to broker and/or supervise the

Figure 1
Multi-granular decomposition of holons in agents and objects

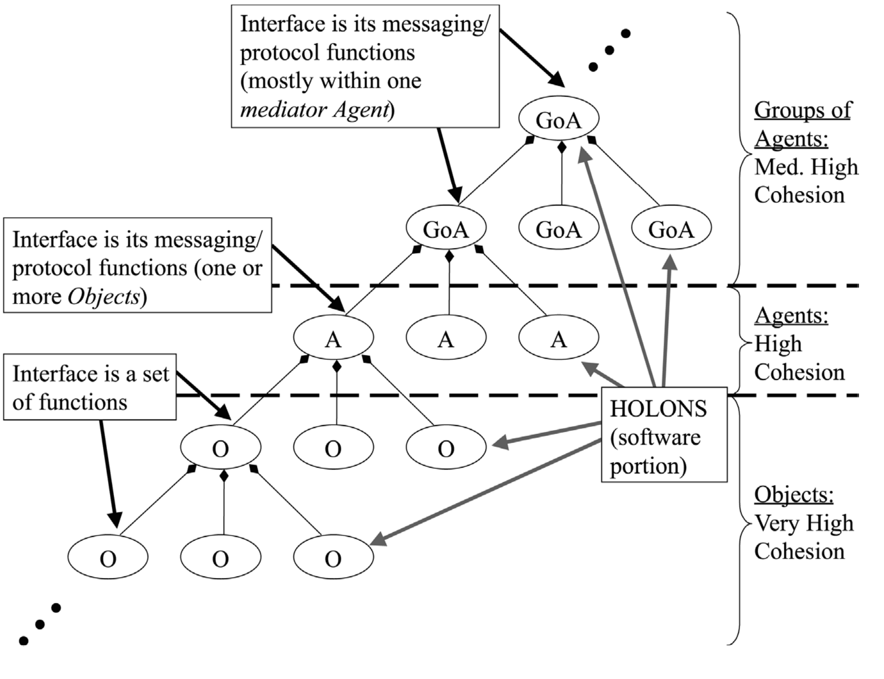
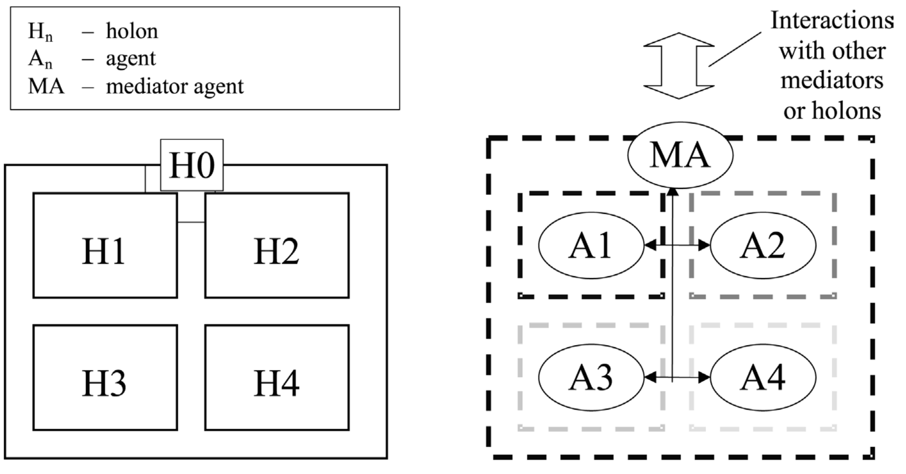


Figure 2
Mapping holonic systems in MAS via mediators



interactions within a group of holons/agents. These groups, or clusters, represent interactions to accomplish a specific task. These interactions can be called a "conversation", and the group of agents/ holons involved can be called a "dynamic virtual cluster" (dynamic because they form and then dissolve as tasks are initiated and then completed, and virtual because they represent a logical or functional decomposition of the system interactions, and not a structural grouping of system components). Dynamic mediators, dynamic virtual clusters, and conversations are all central concepts to the design of manufacturing holarchies (Zhang and Norrie, 1999).

The architectural structure in such holarchies follows the design principles for metamorphic architectures. For example, in Figure 3, physical manufacturing resources (e.g. milling machines, robots, etc.) at the machine level are represented by corresponding software agents (e.g. machine "m1" is represented by agent "1-1"). These agents may then be grouped dynamically at the enterprise level based on the current product line (e.g. using group technology methods). In order to execute specific orders, clones of these agents may now participate in dynamic virtual clusters as illustrated at the top of Figure 3.

In order to facilitate the dynamic virtual clustering process, a pattern of holonic collaboration is followed as is summarized in Figure 4.

Patterns of holonic collaboration

As an organizational paradigm (inspired by the self-organizing properties of natural systems), holonics models social organizations as nested clusters (holons) of sub-organizations (sub-holons) driven towards a common purpose by collaborative rules. The rules act as forces that coordinate interactions between sub-holons working together towards a common purpose. Of crucial importance is that rules ensure coordination with local environment, that is with the other holons and sub-holarchies.

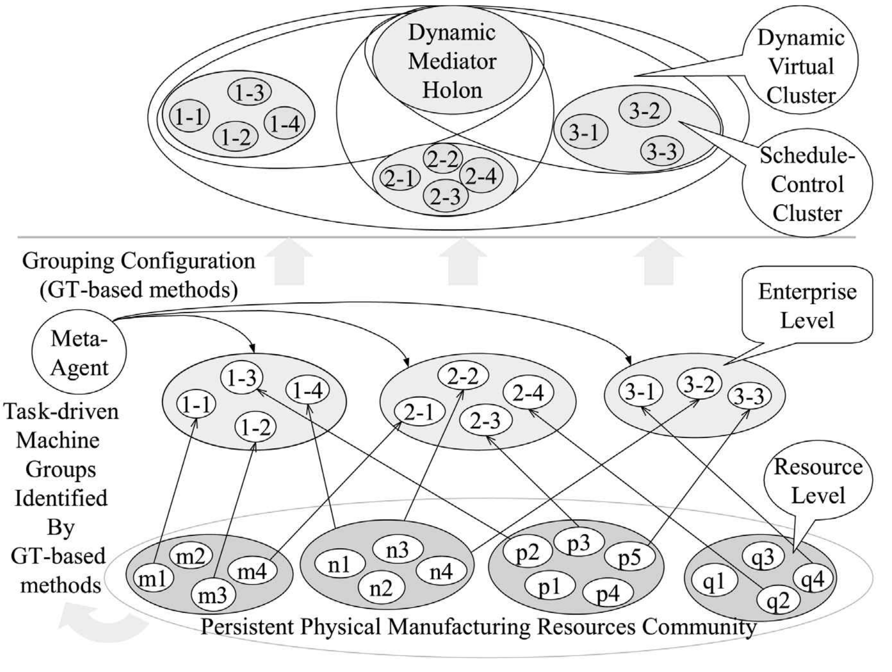
The HE paradigm emerges from the synergetic triad Holonics-MAS-Internet to provide a framework for information and resource management in global virtual organizations by modeling enterprise entities as software agents linked through the Internet. The rules for holons in a HE are co-opetition rules implemented as strategies for negotiation, collaboration, cooperation and other coordination mechanisms. Such rules define the patterns of holonic collaboration according to which the holarchy functions.

The MAS inhabits the environment of computers, controllers, and networks; as such, each agent is part of a holon. Its inputs are the machine's sensors, data from storage, and interactions or communications with other agents and with humans; its outputs are the physical control of machines, data to storage, and interactions or communications with other agents and with humans.

The flexible re-configurable architectural model in Figure 3 is enabled by the synergetic interaction of the following patterns that form the coordination backbone of a HE:

- *Dynamic virtual clustering*. This pattern is facilitated by the general layered architecture of the HE. Each resource consists of control execution (CE), execution control (EC), and execution (E) agents. Details of this machine level model will be described in further detail in the

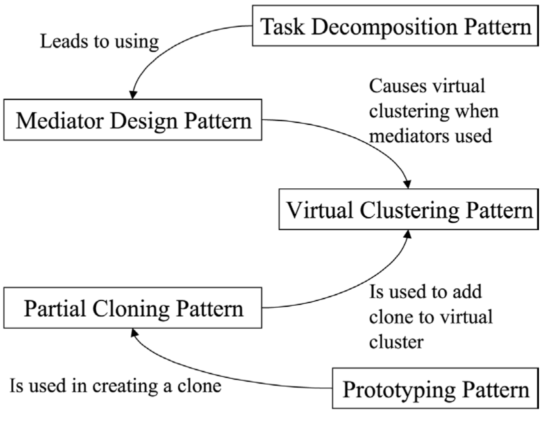
Figure 3
Mediator-based metamorphic architecture



next section. The dynamic virtual clustering pattern plays a crucial role in that it embeds the self-organizing properties of a HE. The main responsibility of this pattern is to configure the enterprise to minimize cost enabling for flexible, re-configurable structures. At all levels of the HE, task propagation occurs by a process of virtual cluster (or holarchy) formation.
- *Mediator design pattern*. The mechanisms supporting the decision-making process that creates and (re)-configures the dynamic virtual clusters of collaborative entities (eventually by adding/removing entities to/from the holarchy to ensure maximal synergy in accomplishing the goal of the HE) are contained in the mediator.
- *Partial cloning pattern*. This pattern defines which of the enterprise's characteristics (attributes and functionality) are abstracted into agents at each level when modeling the HE as a collaborative multi-agent system.

Once the goal of the HE has been determined the mediator clusters the global distributed resources (cloned as agents by the partial cloning pattern) using the mechanisms implemented in the dynamic virtual clustering pattern, such that the goal can be achieved optimally. This is done through the task decomposition pattern (illustrated in Figure 5) that splits the goal into sub-tasks which are distributed across the available resources.

Figure 4
Patterns of holonic collaboration



Task decomposition-distribution pattern

This pattern ensures the workflow coordination throughout the collaborative holarchy ensuring harmonious distribution among the participants the overall task assigned to the collaborative holon, at each level.

The main mechanisms by which this pattern works are:
- *task distribution among the cluster's entities* – outside-in view from the mediator "down" into each collaborative partner at that level; and
- *task deployment within each entity* – inside-out view, from the entity, regarded

as a holon with distributed resources available to it for accomplishing the assigned task, to the mediator.

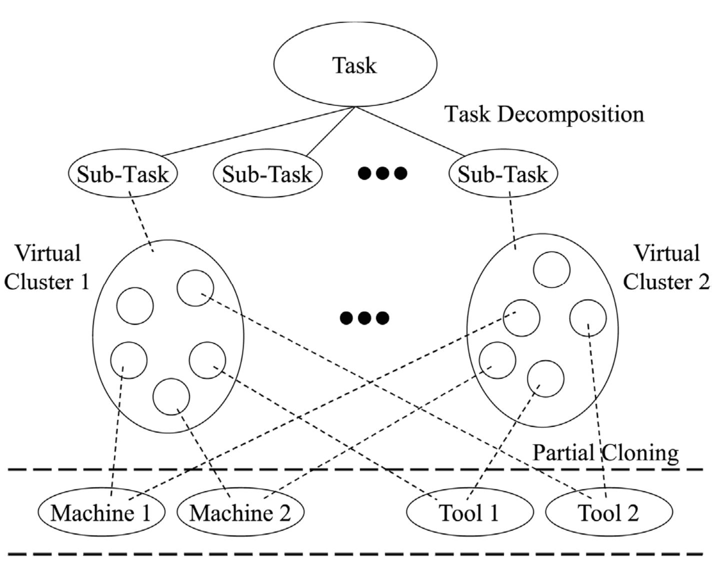
Both mechanisms call for appropriate negotiation strategies (Jennings *et al.*, 2001) to enable appropriate loading of each collaborative partner according to its available resources as well as deadline commitment and delay justification through appropriate argumentation and persuasion strategies. An excellent tool for inducing decentralization into the holonic collaboration is the institutionalized power (Jones and Sergot, 1996) that transfers complete responsibility regarding the "how" of the task's accomplishment to the entity to which the task was assigned once this entity has accepted the delivery conditions.

Propagation of the task decomposition-distribution pattern throughout the granular levels of the HE requires two kind of ontologies to enable 'inter-entity' communication, which define an ontology pattern.

Ontology pattern

This consists of two kind of ontologies:
1 "Peer-to-peer" communication within each level (that is "inter-agent" communication among entities that form a cluster).
2 "Inter-level" communication that enables deployment of tasks assigned at higher levels (by the mediator) on lower level clusters of resources as well as reporting (from the lower level to the higher) of emergency situations for which rescheduling/re-planning reconfiguration are required.

Figure 5
The task distribution pattern



The HE

The general HE model is illustrated in Figure 6. As can be seen in this figure, the HE is a holarchy of collaborative enterprises, where each enterprise is regarded as a holon and is modeled by a software agent with holonic properties, so that the software agent may be composed of other agents that behave in a similar way but perform different functions at lower levels of resolution. The flow of information and matter across the HE defines three levels of granularity:
1 the inter-enterprise level;
2 the intra-enterprise level; and
3 the machine level.

In this section, we describe the models used at each of these levels.

The inter-enterprise level

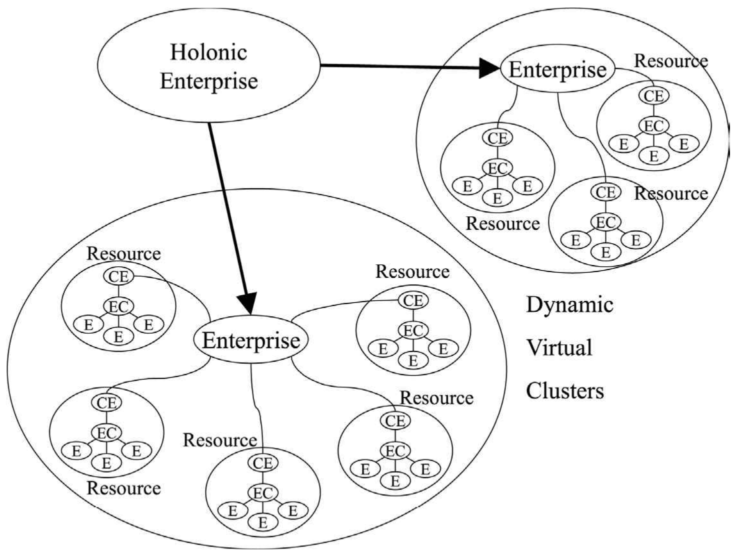
At this level, several holon-enterprises cluster into a collaborative holarchy to produce products or services. The clustering mechanisms embedded in the mediator support maximal synergy and efficiency.

Traditionally, especially in the manufacturing domain, this level was regarded as a mostly static chain of customers and suppliers through which the workflow and information was moving from the end customer who required the product to the end supplier who delivered it. The lag induced throughout the predetermined chain, linking suppliers with long-lasting relationships, was affecting the customer on one side through its inability to accommodate changes in product requirements; on the other side, through its supplier-centeredness that placed the supplier interests above the customer's when it came to timely delivery of products (Fox *et al.*, 1993). Taking advantage of the power of the Internet, the HE model endows the supply chain with flexibility and reconfiguration capabilities intrinsic in the collaborative holarchy paradigm shown in Figure 6. With each collaborative partner modeled as an agent that encapsulates those abstractions relevant to the particular cooperation, a dynamic virtual cluster (illustrated in Figure 3) emerges which can be configured on-line according to the collaborative goals. Such a dynamic collaborative holarchy can cope with unexpected disturbances (e.g. replace a collaborative partner who cannot deliver within the deadline) through on-line reconfiguration of the open system it represents. It provides on-line order distribution across the available partners as well as deployment mechanisms that ensure real-time order error reporting and on-demand order tracking. Thus the static supplier-centered chain becomes a dynamic collaborative holarchy emerging around customer needs to bring together the best suppliers able to satisfy these needs in the best possible way.

The intra-enterprise level

Once each enterprise has undertaken responsibility for the assigned part of the work, it has to organize in turn its own internal resources to deliver on time according to the coordination requirements of the collaborative cluster. For example, in the manufacturing domain, planning and dynamic scheduling of resources at this level enable functional reconfiguration and flexibility via (re)selecting functional units, (re)assigning their locations, and (re)defining their interconnections (e.g. rerouting around a broken machine, changing the functions of a multi-functional machine). This is achieved through a replication of the dynamic virtual clustering mechanism, having now each resource within the enterprise cloned as an agent that abstracts those functional characteristics relevant to the specific task assigned by the collaborative holarchy to the partner. Reconfiguration of schedules to cope with new orders or unexpected disturbances (e.g. machine failure) is enabled through re-clustering of the agents representing the actual resources of the enterprise, as illustrated in Figure 5. The task assigned to each enterprise is distributed on its internal resources via the task deployment pattern, as follows. First the task is split into sub-tasks which can be assigned to clusters of resources belonging to each enterprise. The virtual communities of agents cloning the resources of each enterprise cluster around dynamic mediators generated around each sub-task. The holonic mediator acting at the inter-enterprise level, emulates production to find the optimal configuration of the resource clustering at the lower levels. The main criteria for resource (re)allocation when (re)configuring the schedules are related to cost minimization achieved via multi-criteria optimization.

Figure 6
The holonic enterprise



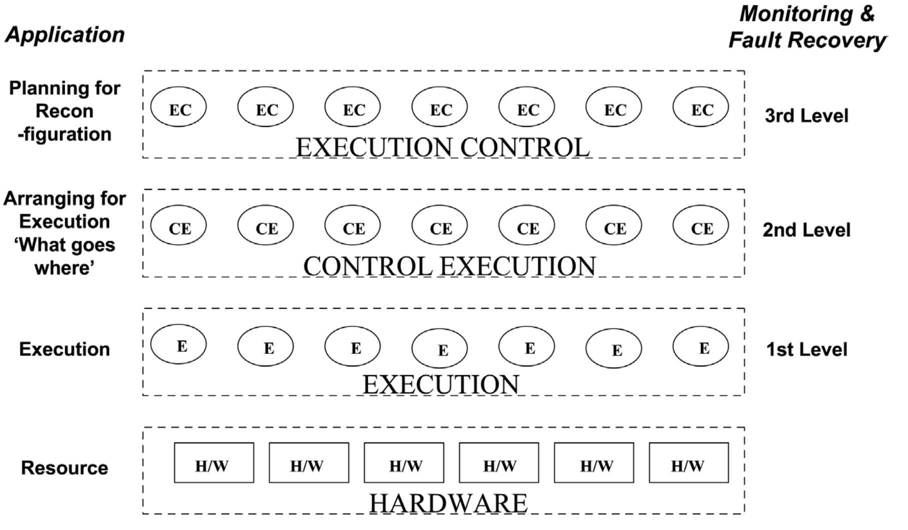
The machine level

In a manufacturing context, this level is concerned with the distributed control of the physical machines that actually perform the work. To enable agile manufacturing through the deployment of self-reconfiguring, intelligent distributed automation elements, each machine is cloned as an agent (Figure 5), which abstracts those parameters needed for the configuration of the holonic control system managing the distributed production.

Once resources are allocated to each sub-task and the production plan configured by the mediators at the inter- and intra-enterprise levels, the schedules of operations are deployed on each resource via the task deployment pattern. In order to decompose the control application management and fault monitoring and recovery tasks in this manner, a multi-layer holonic control architecture is used that consists of the four temporally decomposed layers illustrated in Figure 7: execution control (EC), control execution (CE), execution (E), and hardware (H/W). This architecture reflects the multiresolutional structure of the HE as well as the inter-level ontologies between the intra-enterprise and the resource management levels. As we move down the layers shown in this figure, time scales become shorter and real-time constraints change from soft to hard real-time; as well, the degree of agency decreases (i.e. higher agents are more sophisticated but slower, while lower agents are fast and light-weight). The EC layer is concerned with "high-level" planning issues such as for reconfiguration control. The CE layer is concerned with arranging for the distribution of applications across multiple resources. The E layer is concerned with the execution of the application. The H/W layer is the physical platform, or the resource being controlled.

Although they work at each level to manage the flow of information and materials within the HE, these patterns have specific particularities within each level of the collaborative holarchy. In the sequel, we will identify on a laboratory example these

Figure 7
Multi-layer machine level architecture



particularities and clearly define the policies and services supported by the patterns as well as the mechanisms that would enable their implementation within each level.

A manufacturing enterprise example

In order to illustrate the basic patterns of holonic collaboration within an HE, we focus on an example of a multi-national corporation that manufactures telephones in this section. Building products like telephones or answering machines involves the acquisition and integration of different components and materials, from various manufacturers and suppliers, thus providing a suitable example of a supply chain. For the sake of simplicity, it is assumed that telephones consist of a printed circuit board, a moulded case and transmitter-receiver equipment as components and cables as materials or sub-components. The printed circuit board plant has a supplier of electronic components.

The inter-enterprise level

At the inter-enterprise level of the HE, the notion of a mediator agent to coordinate the high-level elements of the manufacturing holarchy is used. The resulting virtual cluster of manufacturing plants, illustrated in Figure 8, consists of the following elements:

- Telephones manufacturer, consisting of an assembly plant which acquires (via the manufacturing mediator) the necessary components for building these products and assembles them.
- Cable supplier – direct supplier for the main manufacturer.
- Transmitter receiver plant.
- Printed circuit board plant. Has one supplier of electronic components.
- Power adapters plant.
- Moulded cases plant.

This level is emulated via the interactions among the plant agents shown in Figure 8. These agents emulate the roles of the manufacturers listed previously. For example, the assembly plant agent will have two main tasks, "MakeTelephone" and "MakeAnsweringMachine" and the power adapter plant will perform a task called "MakeAdapter". The manufacturing mediator agent coordinates the interaction between the plant agents and makes sure that the customer request is taken care of in due time by interacting (via the assembly mediator) with the order, logistics and transportation agents/holons acting at the next lower level as is illustrated in Figure 9.

The negotiation process is driven by the manufacturing holarchy need for a specific resource. When a resource has been produced or received it is made available to the entity in the collaborative cluster that needs it. Agents know about each other's capabilities through a directory facilitator (DF) (FIPA, 2002) embedded within the manufacturing mediator. To initiate and engage in a transaction dialogue, agents will be equipped with appropriate protocols and abilities that influence their dealings with others.

The intra-enterprise level

At the intra-enterprise level of the HE, the following entities are identified for the assembly plant holarchy illustrated in Figure 9:

- Assembly mediator (encapsulating the logistics functions) responsible for coordinating the collaborators and suppliers by interfacing with the manufacturing holarchy and negotiating the production and delivery of needed resources (components, materials) to fulfill customer requests.
- The customer – who triggers the production and transfer of resources on demand.
- The order manager – responsible for acquiring orders and handling customers' requests.
- Planning and scheduling unit that allocates the enterprise resources and interfaces with the resource level.

Figure 8
Phone manufacturing inter-enterprise holarchy

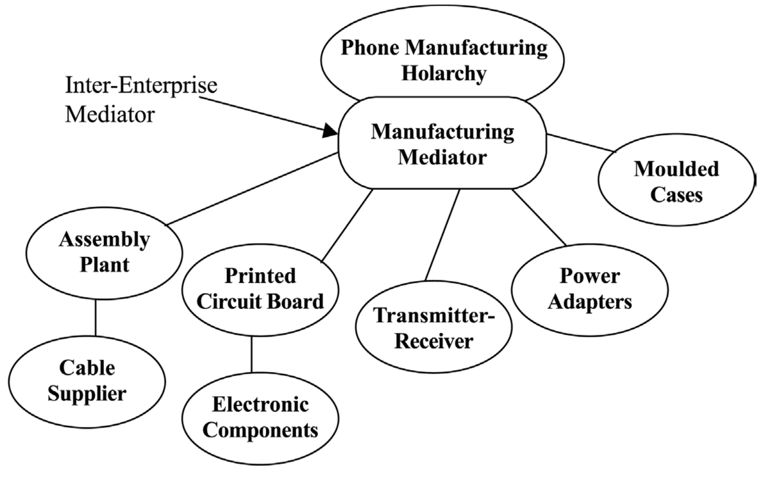
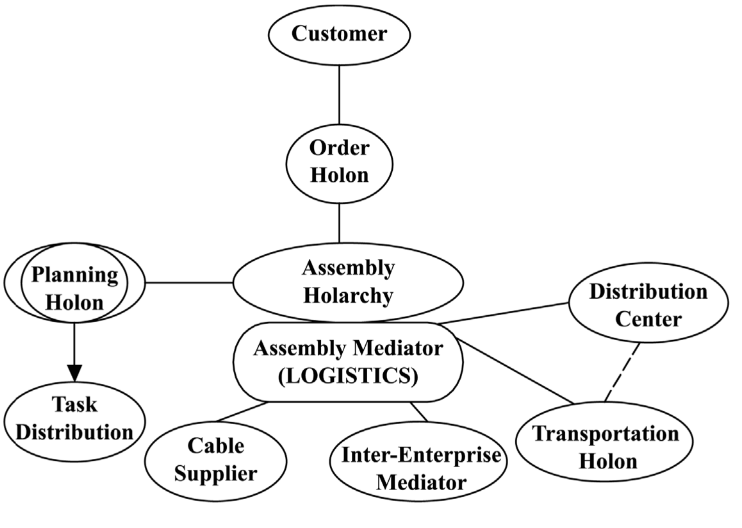


Figure 9
Phone manufacturing intra-enterprise holarchy



- The transportation unit – responsible for the management of transportation resources.
- The distribution centre – that uses the transportation resources to distribute materials and supplies to the assembly sections as needed.

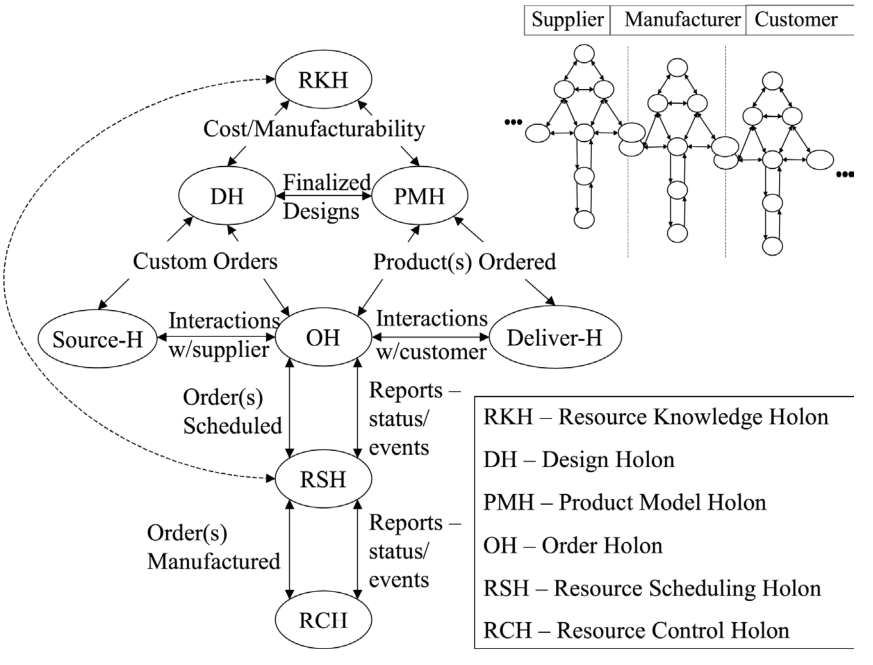
The assembly plant agent/holon decomposes at the intra-enterprise level into the assembly holarchy presented in Figure 9:

- The customer agent (enabled with an interface) acts on behalf of the customer and via the order holon triggers the production and transfer of resources.
- The order holon handles requests from customers, approving orders and getting information regarding the orders.
- The assembly mediator coordinates the plants and suppliers and negotiates the production and delivery of needed resources across the collaborative holarchy to fulfill the order placed by the order holon. For this it closely interacts with the manufacturing mediator.
- The planning holon decomposes into the assembly planning holarchy presented in Figure 10, via which it allocates resources to fulfill the order in due time.
- The transport agents are responsible for the allocation and scheduling of transportation resources required by the logistics agents.

At this level, the collaborative partners are the sections and departments within the enterprise among which the overall task for the enterprise has to be distributed and scheduled. The assembly planning holarchy passes the received orders down to the manufacturing resources from the assembly plant. The resource knowledge holon has an inventory of all available assembly machines as well as the parts available to be assembled. The order holon passes the order received from the customer to the resource knowledge holon (RKH) via either the design holon (DH) or the product model holon (PMH) – depending on the nature of the order.

If products of that kind have been manufactured before by the assembly plant then the PMH will search for the manufacturability model and pass it on to the RKH. If this is a new product then the DH will first create a product model and then pass it to the RKH. The RKH collaborates with the resource scheduling holon (RSH) to allocate the available parts and materials to the available assembly machines in order to build the particular kind of telephones by the due date of the order. To optimize production efficiency and cost the RKH and RSH collaborate closely with the assembly

Figure 10
Assembly planning holarchy



mediator. Once the schedule is in place it is deployed on the assembly machines via the mechanism described in the next sub-section.

The machine level

Any sort of automated matching – between product orders and the resources on which they are to be processed – requires a common ground for comparison. One possibility, used frequently in manufacturing, is to use group technology to provide standardized descriptions for product features and resource capabilities (Bauer *et al.*, 1994), which can allow the determination of product families and resource work-cells/lines and illuminate overlapping resource capabilities for flexible routing of orders. The automated decomposition of products/orders into their constituent features and processes is then possible. This is useful for automated order routing (Walker *et al.*, 2001), as well as for the concurrent design process (Xue, 1999). The dispatching, scheduling, and processing of an order on the resources of our manufacturing assembly example is done via the production holarchy presented in Figure 11.

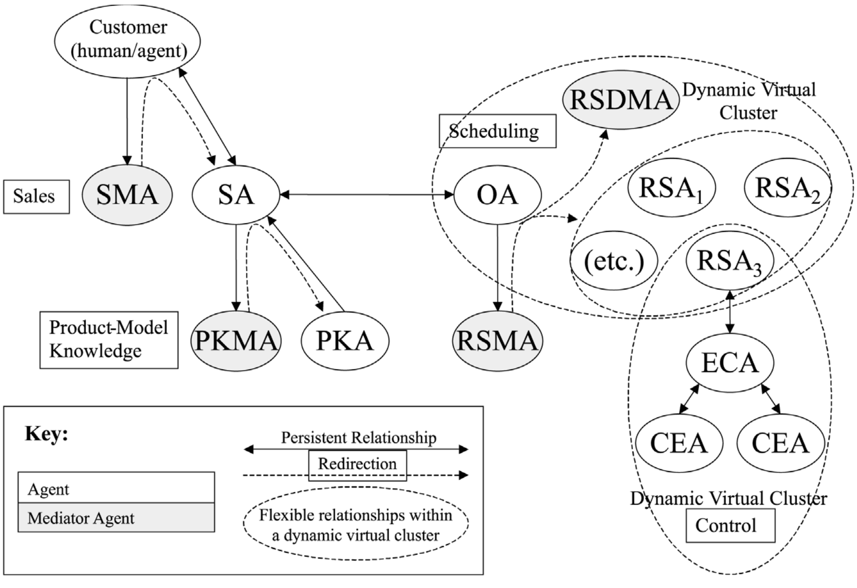
In this Figure, the order is initiated by the customer once an acceptable agreement has been reached with the sales agent (SA). In this case, the customer is directed to the appropriate SA by the sales mediator agent (SMA). The order is then managed by an order agent (OA) as is shown in Figure 11. In order to determine the appropriate resources to execute the order, the OA first consults a resource mediator agent (RSMA), then a dynamic virtual cluster of agents is formed for the duration of the order consisting of the OA and resource agents (RSA). This dynamic virtual cluster is coordinated by a resource scheduling dynamic mediator (RSDMA). Finally, as is shown in Figure 11, each resource is managed using the EC/CE/E agent structure defined in Figure 7.

At this point, we can continue our example at the machine level. The machine level example focuses on a single assembly cell in the assembly plant. As is shown in Figure 12(a), this cell consists of two robots and a conveyor. The task for this cell is to assemble "Model A" circuit boards. To accomplish this, the task is decomposed (by an EC agent) in to robot and conveyor control sub-tasks (that are managed by CE agents), and the appropriate control applications are distributed to the robot and conveyor hardware (as E agents running on the hardware).

Conclusions

Emerging from the synergetic blend of the triad Holonics-MAS-Internet, the HE enables participants in the global market to enter strategic partnerships via the WWW while harmoniously managing the workflow throughout the resulted collaborative holarchy. At the highest inter-enterprise collaborative level, the main shift is from the closed system philosophy of the traditional

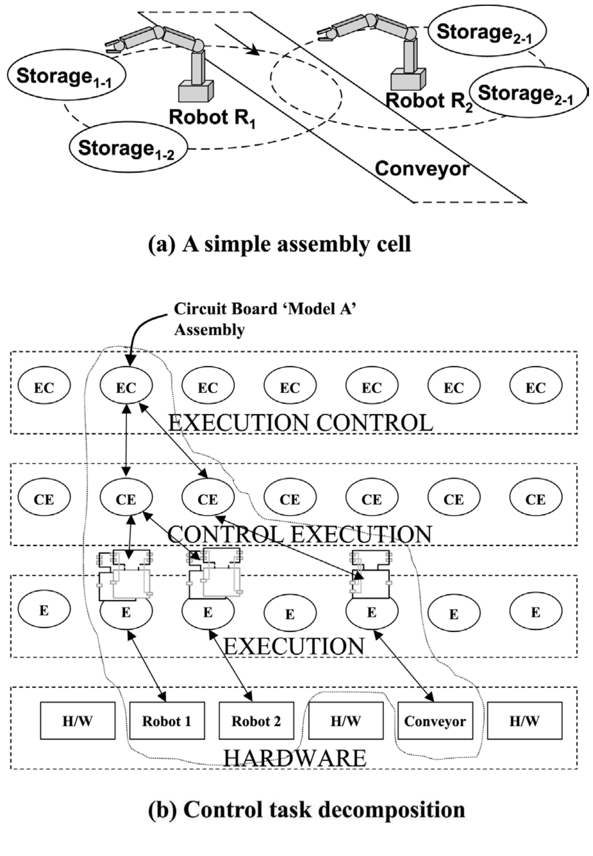
Figure 11
Production holarchy



supply chain management to the open system philosophy governing a collaborative cluster of partners devoted to the same goal. Inside each enterprise the planning and scheduling level transfers the tasks onto the available resources – the lowest level – via dynamic, reconfigurable software technologies, in a manner that also supports monitoring and fault-recovery for order processing. At the physical machine level, recent advances in distributed control system models, software and hardware are used to realize a distributed process automation system with intelligent control components.

There are already several tools that facilitate the implementation of our HE model. Those players that will enter the global networked economy through a gateway to the HE will definitely race with a high competitive advantage. Our current work focuses on the implementation of the HE model presented here for a multi-national corporate manufacturer. This will result in shorter up-front commissioning times as well as significantly more responsiveness to change (e.g., by utilizing the reactive properties of autonomous and cooperative agents) than current SAP and SCADA systems.

Figure 12
Phone manufacturing machine level holarchy



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