Adaptive Information Infrastructures for the e-Society

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Abstract. Positioned at the confluence between human/machine and hardware/software integration and backed by a solid proof of concept realized through several scenarios encompassing e-Securities, e-Health, and e-Logistics for global manufacturing and emergency response management, this work exploits latest advances in information and networking technologies to set a systematic framework for the design of the information infrastructures (coined as AIIs - Adaptive Information Infrastructures) destined to fuel tomorrow's e-Society. Designed following the natural laws of evolution, which merge self-organization and natural selection [38], these socially embedded information infrastructures can adapt to fulfill various needs as their environment demands. Computational intelligence techniques endow the AIIs with learning and discovery capabilities, emulating social and biological behavior. AIIs are destined to become an integral part of our life by supporting, rather than disturbing, a framework that facilitates strategic partnerships while providing greater user-friendliness, more efficient services support, user-empowerment, and support for human interactions.

Keywords. distributed artificial intelligence, information infrastructures, emergency response management, e-Health, Cybersecurities, emergence, self-organization, evolution

1 Rationale

Today's electronic information technologies are linking our world, enabling partnerships otherwise impossible in all areas of our life. From e-Commerce and e-Business to e-Learning and e-Health the economic strategies as well as the routine professional practices have been irreversibly contaminated with the spice of electronic connectivity. Supported by this technological leverage, new paradigms have emerged with models that are dynamic, autonomous, self-organizing and proactive, generically coined as 'intelligent'. In particular Multi-Agent Systems (MAS) have changed the software world, and with it the world of information technologies. With the reasoning encapsulated in *societies of software agents,* having a life of their own in Cyberspace, the In-

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ternet 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.

With this the dawn of the e-Economy is already upon us and as direct consequence the e-Society emerges as a parallel world of information, where people ‘cloned’ as agents are ‘living’ in a virtual 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. Paradigm shifts abound in our world, shaping our lives more and more dramatically. Building on the power of distributed intelligence on the web they swing the driving forces of our economy from competition to cooperation, from individualism to strategic partnering, from power-from-information to authority-from-wisdom, from fear to trust (and, sometimes, vice versa). To secure our future we need to act quickly to take these developments in a safe direction that guarantees the hidden dangers of these technologies are superceded by its positive effects meant to improve our lives. All the right questions spanning ethical and societal concerns have to be posed before our lives immerse into such e-systems to ensure a safe environment is created.

In today’s dramatic context there is an acute need for such new techniques capable to deal with critical aspects such as emergency response management, network, information and national security enhancement, population health and quality of life improvement, etc. In spite of the tremendous progress made by researchers to enable the electronic communication space (be it networked or wireless) to become a Dynamic Service Environment[1] (DSE) supporting all aspects of life, from business and commerce to education and health, society is stagnant, still using the old ways while these tremendous IT advances are not applied. Elderly and remotely located people without possibility of transportation still live in isolation. New threats test us continuously calling for new ways to cope with emergency and crisis situations and for tools that are more dynamic, anticipative and adaptive in real-time. To build more immunity for our world in coping with unexpected disasters (be they natural, such as earthquakes, floods, hurricanes or man-made ones such as oil spills in the ocean, terrorist attacks, etc.) and more recently health emergencies posed by highly contagious diseases (bird flu, SARS, mad cow, etc.) it is of the essence to unleash the power of IT. In such crisis situations there is a high need to react quickly in a reasonable, efficient way to restore the effects of the crisis.

To meet this need we propose a systematic approach to the design and implementation of such dynamic environments supporting coalition formation, which we refer to as *adaptive information infrastructures* (AII). AIIs could glue together the best organizations capable to cooperate in the timely solving of a crisis, and support the coordination of activities across such an extended cooperative organization, getting clarity to emerge from the fog of information and help make the best decisions out of the crisis chaos.

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[1] www.agentcities.org (The Global Agentcities Task Force has the mandate to bring together forces from all continents in a common effort to develop the dynamic infrastructures of tomorrow’s ‘alive’-Web.)

2 State of the art in the design of information infrastructures

Future information systems will use ambient intelligence to create collaborative ecosystems of stationary and mobile devices, such as mobile phones, PDAs, personal mobile gateways, portable players and personal storage devices [1]. These ecosystems will form an environment that supports complex interactions between distributed systems. Multi-agent technology is an excellent candidate for realizing such an environment, but requires the development of methods and technologies for its control, maintenance and evolution. Organization is crucial to this dynamic environment because groups of agents need to communicate with each other and self-organize to meet their objectives.

As information systems become more complex, it is increasingly difficult to manage them using traditional approaches based on centralized and pre-defined control mechanisms. The dynamic configuration of loosely combined artifacts and services puts new requirements on middleware and frameworks, which need to be more adaptive and responsive in real time. One example of a new architectural approach is open resource coalition as a shared infrastructure that automates configuration decisions given a specification of the user's task [2]. They use (like most approaches [3], [4]) analytical models to make near-optimal configuration decisions.

As open-resource coalitions, shared infrastructures are:

- *pervasive/ambient*, available everywhere as an integral part of the environment;
- *intelligent*, in the sense that people will react and respond to AIIs as they would to a human being;
- *adaptive*, with their behavior changing in response to actions in the environment; and
- *anticipatory*, meaning they can anticipate an attack without conscious mediation.

Given their characteristics, AIIs call for a complex approach to their design. Recently, models from biology, the physical world, chemistry and social systems have inspired scholars to seek ways to more efficiently manage complex information ecosystems [5] [6].

To influence the development of this technology in a human-friendly way our approach builds on the natural laws/patterns of self-organization according to which adaptive / intelligent systems emerged in the process of universes' evolution [7]. Our approach [8] addresses this by enabling information infrastructures for various applications. For example, for global production integration [9], we developed a methodology for dynamic resource management and allocation across distributed (manufacturing) organizations [10], [11]. The approach integrates multi-agent technology with the *holonic* paradigm proposed by A. Koestler in his attempt to create a model for self-organization in biological systems [12].

3 Holonics

Koestler postulated a set of underlying principles to explain the self-organizing tendencies of social and biological systems. He 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 as autonomous entities, yet cooperating to form apparently self-organizing hierarchies of subsystems, such as the cell/tissue/organ/system hierarchy in biology.

Starting from the empirical observation that, from the Solar System to the Atom the Universe is organized into self-replicating structures of nested hierarchies intrinsically embedded in the functionality of natural systems, in his attempt to creating a model for self-organization in biological systems, Koestler has identified structural patterns of self-replicating structures, named holarchies. Holarchies have been envisioned as models for the Universe’s self-organizing structure in which holons at several levels of resolution in the nested hierarchy [6] (Fig. 1) behave as autonomous wholes and yet as cooperative parts for achieving the goal of the holarchy.

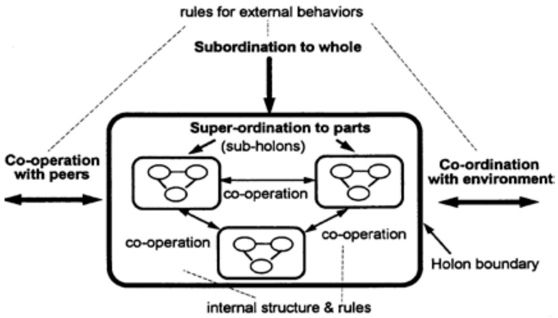

Fig. 1: Generic Model of a Holarchy

In such a nested hierarchy each holon is a sub-system retaining the characteristic attributes of the whole system. What actually defines a holarchy is a purpose around which holons are clustered and subdivided in sub-holons at several levels of resolution according to the organizational dissectibility required. A Confederation is a *political holarchy*, for example having Canada at the highest level of resolution then the provinces at the immediate lower level, and finally the cities at the lowest levels in the hierarchy. Each individual person is regarded as a primitive holon within this social holarchy.

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[2] suitable for modeling holarchies as software systems.

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 greatest challenge faced by holons in a holarchy is ‘the whole in the part’ dichotomy. As autonomous systems (wholes) holons are animated by autonomy and separation forces while being constraint as parts of the holarchy to work

[2] HMS – Strategies, Vol. 1 (Deliverable of WP6, March 1994 – Confidential).

cooperatively with other holons towards the common goal around which the holarchy was formed. 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 [13], [39]. These rules endow the holons with interdependence, namely the capability of integration as parts within the holarchy. Of crucial importance is that rules ensure coordination with local environment that is with the other holons and sub-holarchies.

For example, Canada as a Confederation is a *political* holarchy in which the provincial governments are subordinated to Ottawa while being superordinated to the city governments. Other examples are: a university is organized as an *educational* holarchy comprised of the President's offices, to which faculties (e.g. engineering, science, medicine, etc.) are directly subordinate (under a dean's leadership), to each faculty, in turn various departments (e.g. electrical engineering, manufacturing engineering, civil engineering, etc.) are subordinated under the leadership of a department head; a global enterprise is a collaborative purpose-driven/market-driven holarchy; a distributed manufacturing system is a production-driven holarchy, the organism is a survival-driven holarchy, The Universe is an evolution-driven holarchy.

4. A Mathematics of Emergence

In his seminal book [38] Stuart Kaufmann postulates that life emerged in the Universe through collective autocatalytic processes fueled by self-organization and natural selection. As result of the process of evolution driven by power laws and autocatalicity, emergence endows the dynamics of composite systems with properties unidentifiable in their individual parts. The phenomenon of emergence involves on one side *self-organization* of the dynamical systems such that the synergetic effects can occur and on the other side interaction with other systems from which the synergetic properties can *evolve* in a new context.

In industrial systems a holonic organization is created (see Fig. 1, [13]) as a nested hierarchy, referred to as *holarchy*, of collaborative entities (e.g. resources, people, departments, sections or enterprises) linked through an information infrastructure that defines several levels of resolution [14]. Each entity is a *holon* and is modeled by a software agent [9] with *holonic* properties—that is, the software agent may be composed of other agents behaving in a similar way, but performing different functions at lower levels of resolution.

The flow of information and matter across a holonic organization defines several levels of granularity (Fig. 3) across which we emulate the mechanism of emergence to enable the dynamic creation, refinement and optimization of flexible ad-hoc AIIs as coordination backbones for the distributed organization, capable to bring together the best resources available (within reach) depending on the needs of the particular crisis to be addressed.

As such, the phenomenon of emergence involves two distinct steps, namely:

- *Self-organization* of the dynamical systems such that the synergetic effects can occur

- Interaction with other systems from which the synergetic properties can *evolve*

We integrate emergence into the holonic paradigm [15] to create, refine and optimize AIIs. Self-organization is achieved by minimizing the entropy measuring the fuzzy information spread across the multi-agent system [10]. This will cluster the resources (agents), ensuring interaction between the system's parts to reach its objectives timely, efficiently and effectively. Evolution is enabled by interaction with external systems (agents); for example, via a genetic search in cyberspace that mimics mating with most fit partners in natural evolution [16] or by means of dynamic discovery services [17]. In the sequel we present the essence of our formalism.

4.1. Self-Organization

A multi-agent system (MAS) is regarded as a dynamical system in which agents exchange information organized through reasoning into knowledge about the assigned goal [10]. Optimal knowledge corresponds to an optimal level of information organization and distribution among the agents. It seems natural to consider the *entropy* as a measure of the degree of order in the information spread across the multi-agent system [44]. This information is usually uncertain, requiring several ways of modeling to cope with the different aspects of the uncertainty. Fuzzy set theory offers an adequate framework that requires the use of generalized fuzzy entropy [45].

One can envision the agents in the MAS as being under the influence of an information "field" which drives the inter-agent interactions towards achieving "equilibrium" with other agents with respect to this entropy [10]. The generalized fuzzy entropy is the measure of the "potential" of this field and equilibrium for the agents under this influence corresponds to an optimal organization of the information across the MAS with respect to the assigned goal's achievement. When the goal of the MAS changes (due to unexpected events, such as need to change a peer, machine breakdown, etc.) the equilibrium point changes as well inducing new re-distribution of information among the agents with new emerging agent interactions. This mechanism enabling dynamic system re-configuration with re-distribution of priorities is the essence of the emergent dynamic holonic structure. In this section, we will prove that when the agents are clustering into a holonic structure the MAS reaches equilibrium, which ensures optimal accomplishment of the assigned goal (task).

A. Vagueness Modeling in MAS – The Problem

It is already well known that among the other uncertainty facets, *vagueness* deals with information that is *inconsistent* [46]. In the context of MAS, this means that the clear distinction between a possible plan reaching the imposed goal and a plan leading, on the contrary, to a very different goal is hardly distinguishable. We call *partition* the clustering configuration in which the union of all clusters is identical to the agent set when clusters are *not* overlapping. If the clusters overlap (i.e. some agents are simultaneously in two different clusters) the clustering configuration is called a *cover*. We define a *plan* as being the succession of all states through which the MAS transitions until it reaches its goal. Each state of the MAS is described by a certain clustering configuration covering the agents set. Starting from this uncertain information, the problem is to provide fuzzy models of MAS, useful in selecting *the least uncertain (the least vague) source-plan*.

B. Mathematical Formulation of the Problem

Denote by $\mathcal{A}_N = \{a_n\}_{n\in\overline{1,N}}$ the set of $N \geq 1$ agents that belong to the MAS. Based only on the initial uncertain information, one can build a family $\mathcal{P} = \{\mathcal{P}_k\}_{k\in\overline{1,K}}$, containing $K \geq 1$ collections of clustering configurations, for a preset global goal. Each $\mathcal{P}_k$ ($k \in \overline{1,K}$) can be referred to as a source-plan in the sense that it can be a source of partitions for a MAS plan. Thus, a source-plan is expressed as a collection of $M_k \geq 1$ different clustering configurations covering $\mathcal{A}_N$, possible to occur during the MAS evolution towards its goal: $\mathcal{P}_k = \{P_{k,m}\}_{m\in\overline{1,M_k}}$. The only available information about $\mathcal{P}_k$ is the degree of occurrence associated to each of its configurations, $P_{k,m}$, which can be assigned as a number $\alpha_{k,m} \in [0,1]$. Thus, the corresponding degrees of occurrence are members of a two-dimension family $\{\alpha_{k,m}\}_{k\in\overline{1,K};m\in\overline{1,M_k}}$, which, as previously stated, quantifies all the available information about MAS.

In this framework, we aim to construct a measure of uncertainty, V (from "vagueness"), fuzzy-type, real-valued, defined on the set of all source-plans of $\mathcal{A}_N$ and optimize it in order to select the least vague source-plan from the family $\mathcal{P} = \{\mathcal{P}_k\}_{k\in\overline{1,K}}$:

$$\mathcal{P}_{k_0} = \underset{k\in\overline{1,K}}{\arg\,\mathrm{opt}}\, V(\mathcal{P}_k)\text{, where } k_o \in \overline{1,K}. \quad (1)$$

The cost function V required in problem (1) will be constructed by using a *measure of fuzziness* [6]. We present hereafter the steps of this construction.

C. Constructing fuzzy relations between agents

We model agent interactions through fuzzy relations considering that two agents are in relation if they exchange information. As two agents exchanging information are as well in the same cluster one can describe the clustering configurations using these fuzzy relations. The family of fuzzy relations, $\{\mathcal{R}_k\}_{k\in\overline{1,K}}$, between the agents of MAS ($\mathcal{A}_N$) is built using the numbers $\{\alpha_{k,m}\}_{k\in\overline{1,K};m\in\overline{1,M_k}}$ and the family of source-plans $\{\mathcal{P}_k\}_{k\in\overline{1,K}}$. Consider $k \in \overline{1,K}$ and $m \in \overline{1,M_k}$ arbitrarily fixed. In construction of the fuzzy relation $\mathcal{R}_k$, one starts from the observation that associating agents in clusters is very similar to grouping them into *compatibility* or *equivalence classes*, given a (binary) crisp relation between them. The compatibility properties of reflexivity and symmetry are fulfilled for covers (overlapped clusters), whereas the equivalence conditions of compatibility and transitivity stand for partitions. The corresponding crisp relation denoted by $R_{k,m}$, can be described by the statement: *two agents are related if they belong to the same cluster*. The facts that a and b are, respectively are not in the relation $R_{k,m}$ (where $a,b \in \mathcal{A}_N$) are expressed by "$aR_{k,m}b$" and "$a\neg R_{k,m}b$". The relation $R_{k,m}$ can also be described by means of a $N \times N$ matrix $H_{k,m} \in \Re^{N\times N}$ - the *characteristic matrix* - with elements ($H_{k,m}[i,j]$) being only 0 or 1, depending on whether the agents are or not in the same cluster. (Here, $\Re$ is the real numbers set.) Thus:

$$H_{k,m}[i,j] \overset{def}{=} \begin{cases} 1 \ , \ a_i R_{k,m} a_j \\ 0 \ , \ a_i \neg R_{k,m} a_j \end{cases} , \ \forall i,j \in \overline{1,N} \,. \tag{2}$$

This matrix is symmetric (obviously, if $aR_{k,m}b$, then $bR_{k,m}a$) and with unitary diagonal (since every agent is in the same cluster with itself). It allows us to completely specify only the configuration $P_{k,m}$ (for the proof see [10].)

As such, the relation $R_{k,m}$ defined by the agents' inclusion in the same cluster is uniquely assigned to the clustering configuration $P_{k,m}$ (no other configuration can be described by $R_{k,m}$). Thus, each crisp relation $R_{k,m}$ can be uniquely associated to the degree of occurrence assigned to its configuration: $\alpha_{k,m}$. Together, they can define a so-called α *-sharp-cut* of the fuzzy relation $\mathcal{R}_k$, by using the equality ($=$) instead of inequality ($\geq$) in the classical definition of α - *cut*. Therefore, the crisp relation $R_{k,m}$ is a α -sharp-cut of $\mathcal{R}_k$, defined for $\alpha_{k,m}$.

Consequently, we can construct an elementary fuzzy (binary) relation $\mathcal{R}_{k,m}$ whose membership matrix is expressed as the product between the characteristic matrix $H_{k,m}$,defined by (2), and the degree of occurrence $\alpha_{k,m}$, that is: $\alpha_{k,m}H_{k,m}$. This fuzzy set of $\mathcal{A}_N \times \mathcal{A}_N$ is also uniquely associated to $P_{k,m}$.

If $k \in \overline{1,K}$ is kept fixed, but m varies in the range $\overline{1,M_k}$, then a family of fuzzy elementary relations is generated: $\{\mathcal{R}_{k,m}\}_{m\in\overline{1,M_k}}$. Naturally, $\mathcal{R}_k$ is then defined as the fuzzy union:

$$\mathcal{R}_k \overset{def}{=} \bigcup_{m=1}^{M_k} \mathcal{R}_{k,m} \,. \tag{3}$$

$$\mathcal{M}_k \stackrel{def}{=} \max_{m\in\overline{1,M_k}}\bullet\left\{\alpha_{k,m}H_{k,m}\right\}\in\Re^{N\times N}, \tag{4}$$

where "$\max\bullet$" acts on matrix elements and not globally, on matrices. The equations (3) and (4) are very similar to the *resolution form* of $\mathcal{R}_k$, as defined in [16]. Here however, some $\alpha_{k,m}$ (in general, with small values) can disappear from the membership grades of $\mathcal{R}_k$.

Obviously, since all matrices $\alpha_{k,m}H_{k,m}$ are symmetric, $\mathcal{M}_k$ from (4) is symmetric as well, which means that $\mathcal{R}_k$ is a fuzzy symmetric relation. The fuzzy reflexivity is obvious (non-zero elements of main diagonal). Thus, $\mathcal{R}_k$ is at least a *proximity* relation. The manner in which the degrees of occurrence are assigned to partitions greatly affects the quality of the fuzzy relation. Although all its α-sharp-cuts could be equivalence relations, it is not necessary that the resulting fuzzy relation be a *similarity* one (i.e. fuzzy reflexive, symmetric and transitive). But it is at least a proximity relation, as explained above.

The fuzzy transitivity, expressed as follows:

$$\mathcal{M}_k \geq\bullet \left(\mathcal{M}_k \circ \mathcal{M}_k\right), \tag{5}$$

is the most difficult to ensure. Here "$\geq\bullet$" acts on matrix elements, and "$\circ$" denotes composition of the corresponding fuzzy relations. In case of *max-min transitivity*, this is expressed analogously to classical matrix multiplication, where the max operator is used instead of summation and min instead of product:

$$\mathcal{M}_k[i,j] \geq \left(\mathcal{M}_k \circ \mathcal{M}_k\right)[i,j] = \max_{n\in\overline{1,N}} \min\left\{\mathcal{M}_k[i,n],\mathcal{M}_k[n,j]\right\}, \tag{6}$$

where $i,j\in\overline{1,N}$ and $\mathcal{M}[i,j]$ is the current element of matrix $\mathcal{M}$.

The equations (5) or (6) suggest an interesting procedure to construct similarity relations starting from proximity ones, by using the notion of *transitive closure*. A transitive closure of a fuzzy relation $\mathcal{R}$ is, by definition, the minimal transitive fuzzy relation that includes $\mathcal{R}$. (Here, "minimal" is considered with respect to inclusion on fuzzy sets.)

So far, a bijective map (according to **Theorem 1**) between $\mathcal{P}=\{\mathcal{P}_k\}_{k\in\overline{1,K}}$ and $\mathcal{R}=\{\mathcal{R}_k\}_{k\in\overline{1,K}}$, say T, was constructed:

$$T(\mathcal{P}_k)=\mathcal{R}_k\ ,\ \forall k\in\overline{1,K}. \tag{7}$$

D. The Measure of Fuzziness

The next step aims to construct a measure of fuzziness over the fuzzy relations on $\mathcal{A}_N \times \mathcal{A}_N$, that will be used to select the "minimally fuzzy" relation within the set $\mathcal{R} = \{\mathcal{R}_k\}_{k \in \overline{1,K}}$.

One important class consists of measures that evaluate "the fuzziness" of a fuzzy set by taking into consideration both the set and its (fuzzy) complement. From this large class, we have selected the *Shannon measure*, derived from the generalized Shannon's function:

$$\begin{cases} S : [0,1]^M \to \Re_+ \\ (x_1,\ldots,x_M) \mapsto S(x) \overset{def}{=} -\sum_{m=1}^{M} \left[x_m \log_2 x_m + (1-x_m)\log_2(1-x_m) \right]. \end{cases} \quad (8)$$

This function has a unique maximum (equal by M, for $x_m = 1/2$, $\forall m \in \overline{1,M}$) and 2^M null minims (in apexes of hyper-cube $[0,1]^M$). For example, if $M = 2$, the surface depicted in below is generated. In general, S generates a hyper-surface inside the Euclidean space $\Re^M$, but all its minima are null.

If the argument of this function is a probability distribution, it is referred to as *Shannon entropy*. If the argument is a membership function defining a fuzzy set, it is refereed to as *(Shannon) fuzzy entropy*. Denote the fuzzy entropy by S_μ. Then, according to equation (8), S_μ is expressed for all $k \in \overline{1,K}$ by:

$$S_\mu(\mathcal{R}_k) = -\sum_{i=1}^{N}\sum_{j=1}^{N} \mathcal{M}_k[i,j]\log_2 \mathcal{M}_k[i,j] - \sum_{i=1}^{N}\sum_{j=1}^{N} \left[1-\mathcal{M}_k[i,j]\right]\log_2\left[1-\mathcal{M}_k[i,j]\right]. \quad (9)$$

Obviously, this function also has a unique maximum and all minima null, with respect to variables $\mathcal{M}_k[i,j]$, its dimension being $M = N^2$.

Two main reasons motivate this choice. First, S_μ helps us make a direct connection between "how fuzzy" is a set and "how much uncertainty" it contains. Thus, since S_μ computes the quantity of information of an informational entity, say a fuzzy set, as the estimated uncertainty that the entity contains, the *minimally fuzzy sets* will subsequently contain the *minimally uncertain* information[3]. Secondly, the "total ignorance" (or uncertain) information is expressed by the unique maximum of S_μ, whereas multiple minimum points (actually, the apexes of the hyper-cube) belong to a "perfect knowledge zone" (as less uncertain information as possible). Between "total ignorance" (which, interestingly, is unique) and "perfect knowledge zone" (which is always multiple) there are many intermediate points associated to different degrees of uncertainty in knowledge about the entity.

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[3] Notice, however, that only the vagueness facet of the uncertainty is measured here. Ambiguity requires more sophisticated measures [7].

Moreover, a *force driving towards knowledge* can be determined [10], by computing the gradient of Shannon fuzzy entropy. It is interesting to remark that the amplitude of this force (its norm), expressed as:

$$\left\|\nabla S_{\mu}(\mathcal{R}_k)\right\| = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}\left[\log_2 \frac{1-\mathcal{M}_k[i,j]}{\mathcal{M}_k[i,j]}\right]^2}\ , \qquad (10)$$

increases very rapidly in the vicinity of any "perfect knowledge" point (see Fig. 6(b) above).

E. The Uncertainty Measure

Although a unique maximum of Shannon fuzzy entropy (9) exists, as proven by (10), we are searching for one of its minima. The required measure of uncertainty, V, is obtained by composing S_μ in (9) with T in (7), that is: $V = S_\mu \circ T$. Notice that V is not a measure of fuzziness, because its definition domain is the set of source-plans (crisp sets) and not the set of fuzzy relations between agents (fuzzy sets). But, since T is a bijection, the optimization problem (1) is equivalent with:

$$\mathcal{P}_{k_0} = T^{-1}(\arg\min_{k\in\overline{1,K}} S_\mu(\mathcal{P}_k))\ \textit{, where } k_o \in \overline{1,K}\,. \qquad \textit{(11)}$$

The new problem (11) does not require a special optimization algorithm, since K is a finite number and all minima, although multiple, are null and localized in apexes of hyper-cube $[0,1]^{N^2}$. Problems could appear only if K is very large. In this case, *genetic algorithms* [8] or *annealing algorithms* [9] can be used to find the minimum. According to the previous interpretations, $\mathcal{P}_{k_0}$ is the least fuzzy (minimally fuzzy), i.e. the least uncertain source-plan from the family and the most attracted by the knowledge zone. Its corresponding optimum fuzzy relation $\mathcal{R}_{k_0}$ might be useful in the construction of a *least uncertain plan* of MAS.

F. Emergence of Holonic Clusters

Once one pair ($\mathcal{P}_{k_0}$, $\mathcal{R}_{k_0}$) has been selected by solving the problem (11) (multiple choices could be possible, since multiple minima are available), a corresponding source-plan should be identified. Two choices are possible:

- List all the configurations of $\mathcal{P}_{k_0}$ (by extracting, eventually, those configurations for which the occurrence degree vanished in $\mathcal{R}_{k_0}$):

$\mathcal{P}_{k_0} = \{P_{k_0,1}, P_{k_0,2}, \ldots, P_{k_0,M_{k_0}}\}$.

- Construct other source-plans by using not $\mathcal{P}_{k_0}$, but $\mathcal{R}_{k_0}$.

The α -cuts of $\mathcal{R}_{k_0}$ are the crisp relations $R_{k_0,\alpha}$, for degrees of membership $\alpha \in [0,1]$. The characteristic matrix elements of $R_{k_0,\alpha}$ are defined by:

$$H_{k_0,\alpha}[i,j] \overset{def}{=} \begin{cases} 1 \ , \text{ if } \ M_{k_0}[i,j] \geq \alpha \\ 0 \ , \ \text{otherwise} \end{cases} , \ \forall i,j \in \overline{1,N} . \quad (12)$$

Each matrix $H_{k_0,\alpha}$ in (12) generates a unique clustering configuration of agents over $\mathcal{A}_N$. Thus, two categories of source-plans emerge: *equivalence* or *holonic source-plans* (when $\mathcal{R}_{k_0}$ is a similarity relation) and *compatibility source-plans* (when $\mathcal{R}_{k_0}$ is only a proximity relation).

- When the associated fuzzy relation $\mathcal{R}_{k_0}$ is a *similarity* one, then an interesting property of the MAS is revealed: clusters are associated in order to form new clusters, as in a “clusters within clusters” holonic-like paradigm [2].

4.2 Evolution

In the open environment created by the dynamic Web opportunities for improvement of an existing virtual organization arise continuously. New partners and customers alike come into the virtual game bidding their capabilities and money to get the best deal. Staying competitive in this high dynamics requires openness and ability to accommodate chance rapidly through a flexible strategy enabling re-configuration of the organization to be able to respond to new market demands as well as to opportunities (e.g. in playing with a better partner when needed.) In response to this need we have designed an evolutionary search strategy that enables the virtual organization to continuously find better partners fitting the dynamics of its goals as they change according to the market dynamics.

A. Selection Pressure in Cyberspace

We regard ‘the living Web’ as a genetic evolutionary system. Our construction is based on the observation that the search process on an *agent domain* containing information about a set of agents that ‘live’ in the Web is analogous to the genetic selection of the most suitable ones in a population of agents meant to ‘fit’ the virtual organization goals. The mutation and crossover operators (p_m and p_c) represent probabilities of finding ‘keywords’ (describing the attributes required from the new partners searched for) inside the search domain considered.

The main idea is to express the fitness function (measuring how well the new agent fits the holarchy’s goal) in terms of the fuzzy entropy (9):

F = S_μ (13)

With this, minimizing the entropy across the extended MAS (which includes the agents from the search domain) according to HE goal-reach optimization equates optimizing the fitness function which naturally selects the best agents fitting the optimal organizational structure of the HE. In the sequel we present the mathematical formalism for this evolutionary search.

B. A Fuzzy Measure for Search Relevance Evaluation

The first step in our construction is to define a measure of relevancy for the search of new agents, based on which partners that better fit the HE goal-reach optimum can be found on the Web to replace the existing ones that are less suitable. That is:

$$S_\mu' < S_\mu \quad (14)$$

where S_μ' is the entropy for the HE with the new partners and S_μ - for the initial HE. According to (7), (8) collapses into

F' < F (15)

(where F' is the fitness function for the HE with new partners) meaning that the new partners better fit the system's goal-reach.

In the previous Section we have proven that minimizing S_μ leads to a fuzzy relation that encodes the best clustering configuration for the HE. This fuzzy relation being either a proximity or a similarity measure it is intuitive to consider it as a good measure for the relevancy of the new agents to the HE goal-reach. Defining for example the fuzzy relation $\mathcal{R}_k$ in (3) as a preference relation encoding, e.g. the desire of agents to work cooperatively, gives a relevancy measure that perfectly fits the purpose of the search for better partners. That is – when agents are found for which the preference is higher then for the existing ones, they should replace the old ones. This increases the membership values of the preference relationship, which indicates that the relevance relative to our search is higher. So defining $\mathcal{R}_k$ as a preference relationship, leads to the following definition of the relevancy measure R:

$$R = \mathcal{R}_{k_0} = \arg\min_{k \in \overline{1,K}} S_\mu(\mathcal{R}_k) \quad (16)$$

From (16) it results that the higher the preference, the smaller the entropy (and accordingly the fitness (13) of the new agents into the holarchy).

C. The Dynamic Web Regarded as an Evolutionary System

With this we are ready to present the algorithm that searches for better partners in Cyberspace. We initialize the search process as follows:

(a) The initial population (*phenotype*) consists of the existing agents in the HE before the search.
(b) Calculate R for the phenotype
(c) Rank the preferences and determine the optimal source plan (11) by computing the corresponding α -cuts.
(d) The preferences for the optimal source plan represented as binary strings constitute the *genotype*. They encode all the relevant information needed to evolve the HE towards a better structure by selecting better agents while searching on an expanded domain.
(e) The phenotype evolves by reproduction according to how the probabilities of mutation and crossover (p_m and p_c) affect the genotype [48]. Each chromosome of the population (in the genotype) will be randomly affected.

We define p_m and p_c to be the probabilities of finding agents in Cyberspace that better fit the HE context. Such agents will have higher preferences (10) then the ones in the phenotype. Michalenicz [49] has proven experimentally that e.g. choosing $p_m \leq 1\%$, $p_c = 20 \div 30\%$ leads to convergence of the genetic algorithm. With this the evolutionary search, is done as follows:

(f) Define the goal of the search as maximizing R that is: select those agents for which preferences are higher then the highest existing ones, and replace by them the agents with lowest preferences.

(g) Define the search domain, e.g. a standard FIPA agent domain (see footnote 7)[4].

(h) The search process on the chosen agent domain is done by genetic selection of the agents that have highest preferences (using to any classical genetic algorithm [48]).

(i) Once the agent domain has been entirely explored a new search is carried on for the next agent domain recommended by the yellow page agent.

[4] The agent domain can be chosen by a yellow page agent [11].

The essence of this evolutionary search process stems from the recursive modification of the chromosomes in the genotype in each generation while monitoring the fitness function (13). At each iteration (that is whenever a new agent domain s searched) all members of the current generation (that is the existing agents in the holarchy and the new ones searched for) are compared with each other in terms of the preference measures. The ones with highest preferences are placed at the top and the worst are replaced with the new agents. The subsequent iteration resumes this process on the partially renewed population. In this way the openness to new opportunities for continuous improvement in the HE constituency is achieved and with this the emergence of an optimal structure for the holarchy. Embedding this strategy in the mediator (Fig. 3) endows the HE with the capability to continuously evolve towards a better and better structure by bringing to the table better and better partners as they are found.

5 Emergent Virtual Organizations

Considering virtual enterprises as holarchies of web-glued organizations, which are modeled as MAS - naturally leads to the concept of *holonic enterprise (HE)*. Thus a HE (Fig. 3) 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. There are three generic levels of resolution within the HE holarchy [14]:

- Inter-enterprise level

At this level several holon-enterprises cluster into a collaborative holarchy to produce a product or service. The clustering criteria support maximal synergy and efficiency. Traditionally 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 that required the product to the end supplier that delivered it. In the HE the *supply chain* paradigm is replaced by the *collaborative holarchy* paradigm. With each collaborative partner modeled as an agent that encapsulates those abstractions relevant to the particular cooperation, a dynamic virtual cluster emerges that can be configured on-line according to the collaborative goals.

- 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. 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

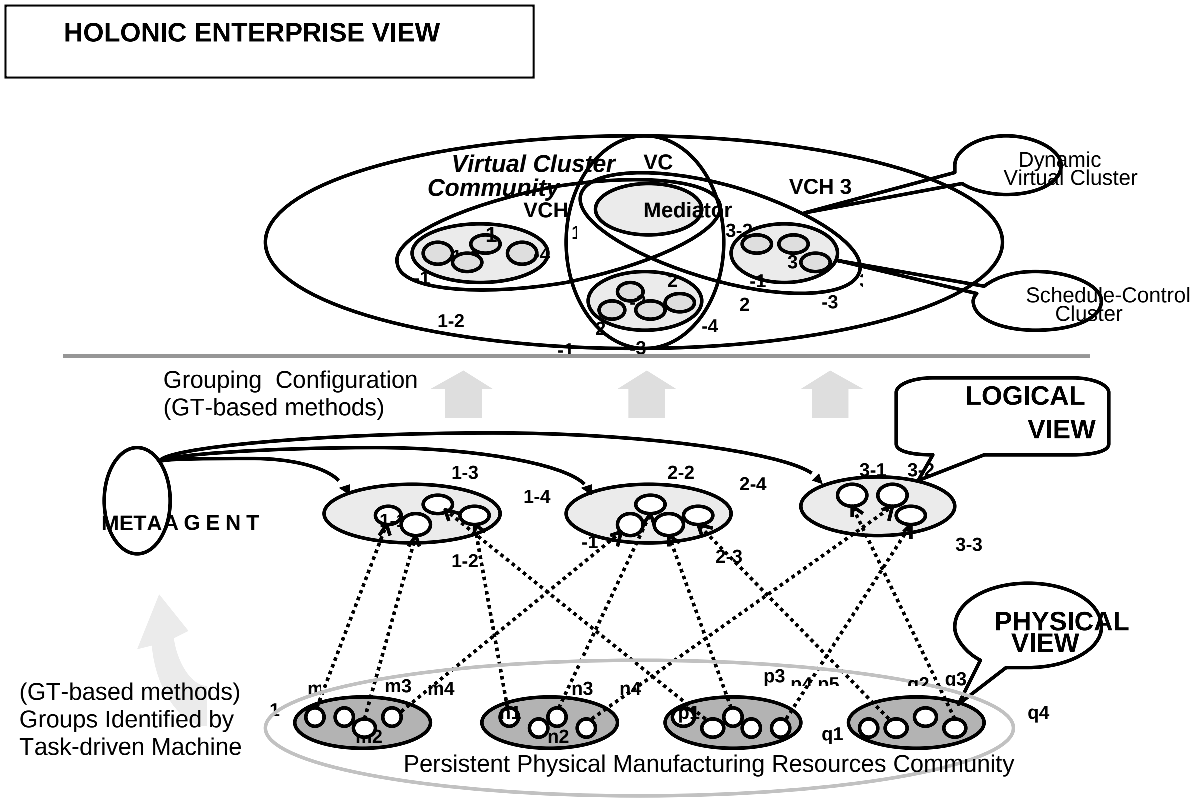


Fig. 3: The three views of a Holonic Enterprise (physical, logical and holonic)

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.

- Basic resource level

To enable the resource management through the DSE each resource (machine; human; information entity) is cloned as an agent that abstracts those parameters needed for the configuration of the holonic production system. Thus the HE paradigm links the three levels of a global collaborative organization to build a web-centric ecosystem partnering in which the workflow is harmoniously managed through the dynamic information infrastructure (the logical view in Fig. 3) that links the resources of all involved organizations (the physical view in Fig. 3).

6 Applications of AIIs

6.1. AIIs for global manufacturing

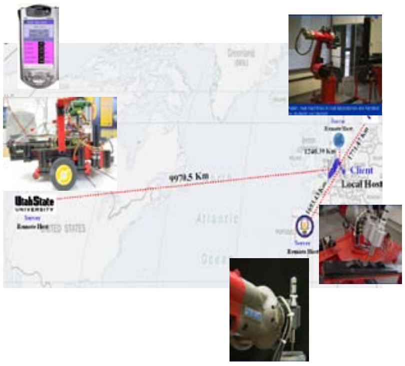


Fig. 4. Global Manufacturing Holarchy

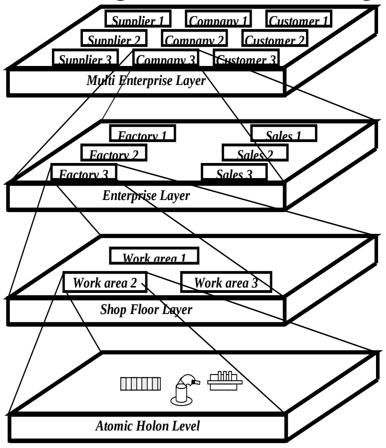


Fig. 5. Layers in Holonic Manufacturing

Our work with the Holonic Manufacturing Systems (HMS) consortium demonstrated that this methodology is very useful for global supply chain management systems that integrate collaborative workflow techniques [18]. Within this context AIIs can be viewed as information ecosystems composed of collaborative but autonomous holons Fig. 4 working e.g. to create a new product by merging several specialized companies and coordinating their efforts, Fig. 5 (from [18]).

The interaction between distributed enterprises, with their suppliers and customers is modeled at the multi-enterprise level. The enterprise level hosts co-operation between entities belonging to one organization, the sales offices and the production sites. The distributed manufacturing control within a production site or shop floor is handled by the shop floor level. Here the entities are distributed work areas working together and in co-operation, in order to fulfill all orders allocated to them. The basic level (the Cell) models the interactions between equipments and humans. In [18] we focused on a supply chain scenario from the phone manufacturing industry. This approach can easily be expanded to any goods distribution networks (e.g. the Wal-Mart supply chain). Figure 6 presents the overall holarchy integrating both inter and intra- enterprise levels.

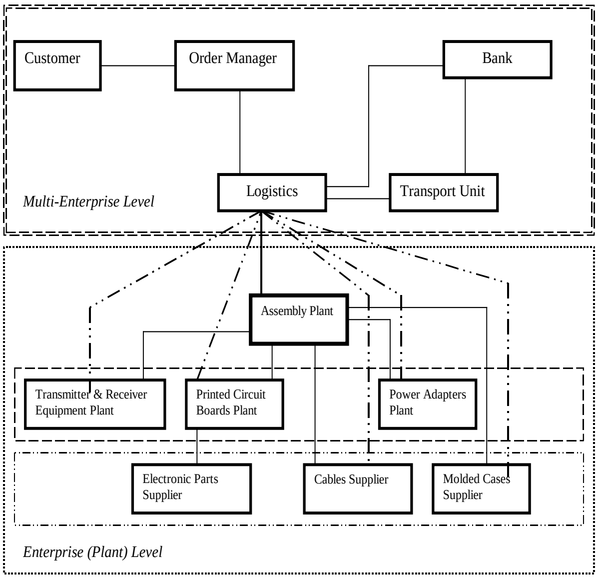


Fig 6: The Supply Chain Holarchy

Having defined the entities involved in the overall holarchy and established the roles and their interactions within the supply chain application, we can create a network of agents (Fig. 7) based on the responsibilities that come from these roles and the resources that need to be produced or consumed.

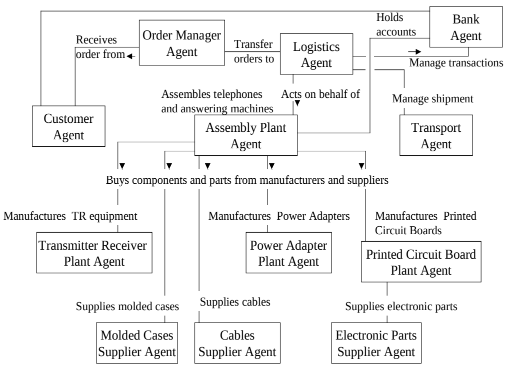


Fig. 7: Conceptual Model of Supply Chain Agents

Figure 8 shows the agent class structure of the Customer agent class, that extends the core agent of the JADE platform (www.fipa.org) thus inheriting all the functionalities that it needs to setup, register, shut down, communicate, and so on.

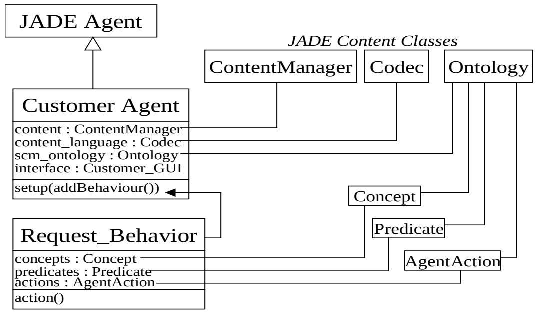


Fig. 8: Class Structure of Customer Agent

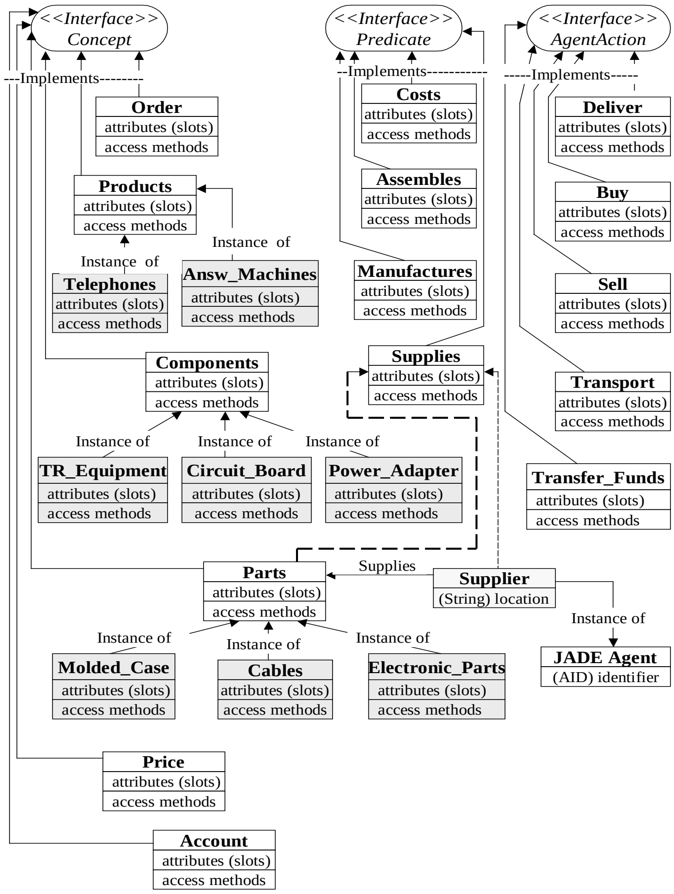


Fig. 9: Dependency relationships in the supply chain domain ontology

More details about the ontology (Fig. 9) and our system's implementation can be found in [18].

6.2 Challenges in implementing AIIs for global manufacturing

The main challenges to be faced here pertain to the vertical integration between levels, where different ontologies have to communicate.

- The main barriers at the real-time control level result from the difficulty of implementing MAS concepts in a stochastic environment where hard real-time constraints must be met to achieve safe system operation.
- Need for optimal clustering (i.e. always group the best partners) – requires on-line reconfiguration of the collaborative cluster to respond to changes in market demands as well as to the needs for maintaining optimal configuration.
- Need to balance the autonomy of each individual partner with the cooperative demands of the collaborative cluster – through negotiation that can range from simple bidding (proposal and counter-proposal) to complex argumentation and persuasion strategies. An example of the latest: the cluster sets a deadline and requirements to coordinate among the partners while partners need to argue their position and integrate the deadline with their other priorities). The cluster sets the 'rules of the game' through component protocols. Preferences can be captured via a utility function such that clustering best partners can be achieved via cost minimization.
- Need for safety. To achieve a safe system, typically two general concepts are used. First, safety channels (i.e., fault monitoring and recovery code) are separated from non-safety channels (i.e., control code). This decomposition technique is typically referred to as the "firewall concept". Second, redundancy is applied in the system in the form of homogeneous redundancy where clones or exact replicas of code are used (only to protect against random failures), or in the form of diverse redundancy where different means are used to perform the same function (this protects against random and systematic failures).
- Need to manage timing and precedence relationships while executing the distributed functions and tasks.
- Need for the system to be capable of arranging for compiling of the code into low-level application code and distributing of this application code to appropriate resources for execution.
- Need to enable the user to develop an application using basic and composite function blocks and application prototypes (templates) from a library.
- Need for monitoring and fault recovery. The purpose of monitoring is to ensure that the control system performs as intended, or in other words, that no latent faults occur. When monitoring for faults, the control system should watch for failures (events occurring at specific times), and errors (inherent characteristics of the system). The types of responsibilities that our control system will have in this area are: diagnosis of program execution, monitoring for exceptions that are thrown by function block code during execution, and monitoring the system state for inconsistencies (e.g., deadline control).

6.3 AIIs for Emergency Response Management

More recently, we successfully took the holonic concept out of the factory environment by designing a holonic framework suitable for emergency response applications [19]. For this testbed (Fig. 10 – from [28]) the actors are either a policeman with a PDA, a firefighter with a cell phone or even a helicopter sending real-time information about the traffic jams to our planner holon. For example, it can indicate an optimal or improved route for emergency vehicles to follow or even more, it will be able to instruct the policemen to clear a road so the firefighters will be able to arrive to the building faster. In case of a bigger disaster our system will be able to contact the hospitals in the zone and start distributing the patients according to bed availability. The emergency AII is depicted in Fig. 11 with three nested levels:

Inter-Enterprise Level: This is the level on which the emergency AII is formed. Each collaborative partner is modeled as an agent that encapsulates those abstractions relevant to the particular cooperation. The "Emergency Mediator" handles the communication process between them. This will require the development of ontologies that will handle the different kind of information exchange and also will allow the system to be expanded.

Intra-Enterprise Level: Before an enterprise/organization can undertake responsibility for some subtask, it has to find out about its own internal resources to ensure that it can deliver on time according to the coordination requirements of the ad-hoc created collaborative cluster.

Atomic Autonomous Systems or Machine Level: The lowest level is the atomic autonomous systems or device/resource level, concerned with the control and coordination of distributed resources performing the work.

Planning and dynamic scheduling of resources on all levels of the emergency holarchy enable functional reconfiguration and flexibility via (re)selecting functional units, (re)assigning their locations, and (re)defining their interconnections (e.g., rerouting around a fire crew, changing the functions of a multi-functional defense unit, reallocating hospital beds to cope with the victims of the crisis, etc.). For details see [29].

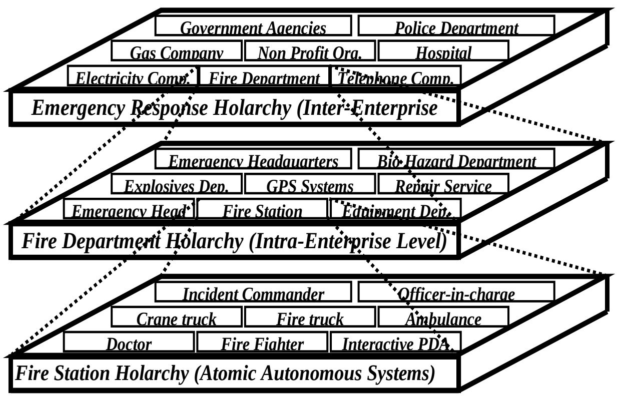


Fig. 11. Emergency Response Holarchy (AII)

During an AII-enabled rescue operation (Fig. 4), novel e-Health technologies can be used, e.g. for patient are authentication by a wireless fingerprint sensor that accesses their profile from a remote database. Depending on indicators such as blood pressure and the health history of the patient, a first diagnosis will be compiled using automated decision support systems [27]. Electronic logistics support will provide information about the next available and suitable hospital, initiate staff assembly and emergency room preparation, and provide on-the-fly patient check-in. Planning and scheduling of resources on all levels of the emergency holarchy (Fig. 11) will enable reconfiguration and flexibility by selecting functional units, assigning their locations, and defining their interconnections (e.g. reallocating hospital beds to cope with the victims, rerouting around a fire crew or changing the assignments of a multi-functional defense unit).

As emergent dynamic information infrastructures that are autonomous and proactive, AIIs can ensure ubiquitous (optimal) resource discovery and allocation while at the same time self-organizing their resources to optimally accomplish the desired objectives. This is achieved through dynamic virtual clustering mechanisms acting on each resource within the enterprise, cloned as an agent that abstracts those functional characteristics relevant to the specific task assigned by the collaborative conglomerate to each unit. Once a crisis arises an AII emerges clustering available resources (modeled as software agents) to deal with the situation optimally.

6.4 Challenges in Implementing AIIs for Emergency Logistics

- To find an optimal cluster is NP-hard. By exploiting heuristics/experiences we aim to overcome the limitations of existing approaches, especially regarding the timely response constraint required by emergency.
- In emergency logistics, where the scope of possible organizations/tasks/skills is not restricted and/or predefined, it is difficult to express and code enough real world semantics to permit a goal-driven and effective communication between levels. Another crucial issue: to incorporate solid trust and reputation mechanisms in agents (e.g. institutionalized power).
- In such dynamic, intrusive environments organizations need to be protected by strong security mechanisms, exceeding today's web-service deployment standards. We will continue work with the FIPA 'Securities' Technical Committee on this issue. A possible solution is *the electronic institution* - a normative framework which emulates regulatory mechanisms in real life social institutions. Such institutions define and police norms that guide individual agents collaborating through AIIs.

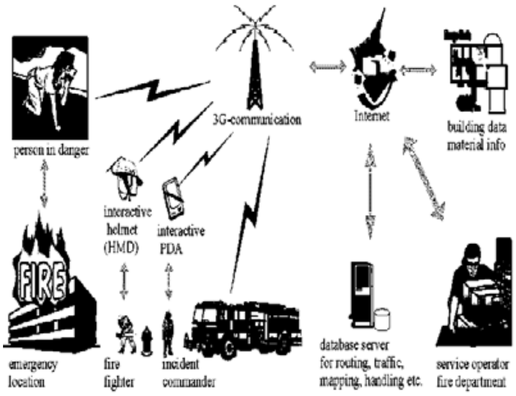


Fig. 10: Fire Emergency Scenario

These norms set acceptable actions that each agent can perform in connection to the role(s) it plays and clearly specifies access restrictions on data according to these roles.

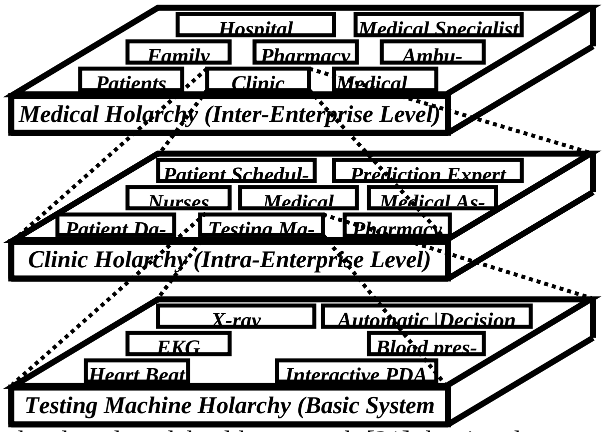
6.5. Scalable Secure Web Based Services for e-Health

We propose a holonic framework suitable for e-health applications. In [20] we defined the concept of medical holarchy as an open evolutionary health system that is highly self-organized and self-adaptive. The collaborative medical entities (patients, physicians, medical devices, etc.) that work together to provide a needed medical service for the benefit of the patient form a medical holarchy. The levels of a medical AII are (Fig. 12):

- ***Inter-Enterprise***: Hospitals, Pharmacies, Medical Clinics/Laboratories
- ***Intra-Enterprise***: Sections/Units/ Departments of each medical enterprise
- ***Resource Level***: Machines for medical tests, medical monitoring devices, information processing resources

In this system of collaborative medical entities new devices and services (Fig. 13) can integrate themselves, offer their functionality to others and share data on a secure level. The complex interaction of diagnosis, treatment and monitoring is made possible through task planners and schedulers that are distributed, automatic and self-configuring.

A major issue in e-Health technology adoption is reconciliation of the various standards of care across the continents. As well the security and privacy of electronic medical records is of major significance and has proven to be the major brake that slowed down the adoption of e-Health by major clinics around the world but especially in the North Americas. Therefore our goal is to develop a reusable framework for secure high-performance web-services in e-health. As a testbed for the secure AII to be developed we will use it to connect a network of medical experts that will collaborate via the AII to develop standards of care for glaucoma [24]. To enable the collaboration of highly specialized glaucoma surgeons located across the country we have developed a telehealth approach [21] that involves a consensus analyzer synthesizing expert opinions into standards of care [22].



Recently we successfully applied this concept to improve glaucoma monitoring [23] with a security layer. This has encouraged us to expand the holonic concept to other e-Health areas that require the dynamic creation of organizational structures and workflow coordination, such as rescuing people after an accident or disaster. This is a time critical operation that requires quick diagnosis, identification of the closest available hospital and knowledge of traffic conditions.

During an AII-enabled rescue operation, novel e-Health technologies can be used, e.g. using biometric technologies [36] for patient authentication by a wireless fingerprint sensor that accesses their profile from a remote database. Depending on indicators such as blood pressure and the health history of the patient, a first diagnosis is compiled using automated decision support systems [25]. Electronic logistics support provides information about the next available and suitable hospital, initiate staff assembly and emergency room preparation, and provide on-the-fly patient check-in.

6.6. Challenges in Implementing e-Health AIIs

The main challenges to be addressed in the implementation of medical holarchies are:

- Need for development, dissemination and utilization of common communication standards, vocabularies and ontologies. Unfortunately there is not much work in this direction and we will intensify our influence in creation of appropriate e-Health ontologies by working with the standard bodies focused on e-Health. For our approach which uses the DOGMA system please see [26].
- Besides the social acceptance of medical holarchies, professional acceptance – that is by the medical doctors is a major issue. We hope that our scenarios will increase the confidence of medical personnel in such technologies by proving their usefulness. Health care professionals are quite reluctant to accept and use new technologies. In the first place, they usually have a very busy schedule, so they lack the time to be aware of the latest advances in technologies and how they could be used to reduce their workload. They refuse to use new tools if they are not integrated smoothly into their daily workflow. They also often mention the lack of time and personnel to convert all the required medical data into an electronic format, so that it can be easily accessed and managed[5]. Some doctors also mention the "hype" built around Artificial Intelligence and, especially, expert systems, twenty years ago, which did not live up to their expectations, and they may reasonably argue that the "intelligent autonomous agent" paradigm, so fashionable today, may also fail to deliver real world results.

We will address these challenges when developing the medical AIIs as a primary response to the needs and requirements of today’s healthcare system, especially to the need for ubiquitous access to healthcare services and ease of workflow management throughout the medical system.

[5] Medical records are usually hand written and distributed in different departments of a medical centre.

6.7. Holonic Cybersecurity System

Information infrastructures are critical to the functioning of society; however, they are vulnerable because of threats and complex interdependencies [31]. New research in this field needs to account for these security issues, which are crucial to future information systems and services. In this context, AIIs provide new dimensions to security:

- *Reliability* of critical infrastructure with survival capabilities, such as power and water distribution.
- *Resilience* based on an anticipative environment that enables operation under continuous threats and attacks.

The issue of Cybersecurity is very difficult to tackle, given that nobody owns the Internet and there is no single 'command post' to control its security. The status quo regarding intrusion detection raises many challenges:

- Post attack information accumulates through many different organizations; therefore ID tools are unable to interact, making correlation of results difficult.
- Incident responses are local. There is no unified mechanism for analyzing such informational alerts and determine their implications/risk factor.

This places on the 'wish list' for security systems the following demands:

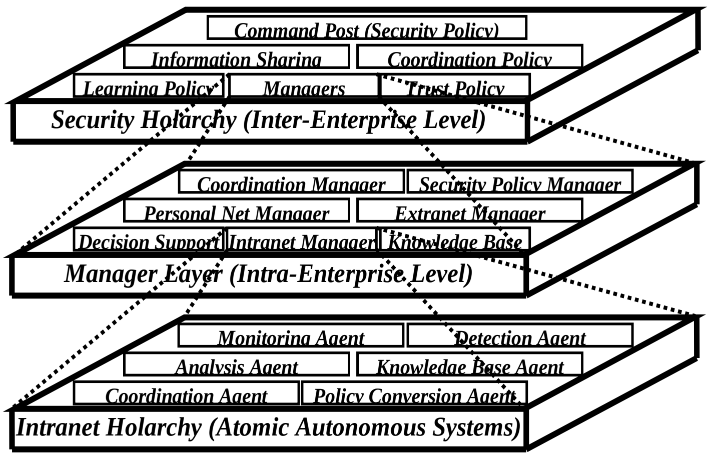
- 'On-the-fly' system configuration, requested by the continuous network changes
- Timely detection of *all kinds* of attacks
- Prevention (and counter-attack) in *any network place*
- Universal installation and maintenance

Most approaches to cybersecurity focus mainly on system protection against known attacks [32], leaving it vulnerable to the myriad of creative intrusion-hackers that produce new viruses daily. Given that today's content inspection techniques use a set of known signatures leaves the question 'How can we deal with unknown attacks?' still open.

Few approaches are taking an anticipative view, by emulating the way biological organisms protect themselves [33], [34]. AIIs are networks with moving objects and subjects 'cloned' as intangible agents in cyberspace. This vision of security cannot be defined top-down. In this ever-changing environment, security policies must evolve and adapt to suit the circumstances. Some of the requirements for the design of Cybersecurity mechanisms meant to protect our information are:

- Coordination in analysis, alerts, incidents management, counteract and response;
- Scalable, continuous running, fault tolerant, self-monitoring mechanisms;
- Ability to detect new kind of attacks;
- Ability to anticipate attacks;

To cope with these needs, we propose a holonic cybersecurity model that emulates biological behavior by inducing immunity into the network or system under attack. Much like Noria et.al. realize network immunity in [37], our system is organized as a holarchy distributed throughout the network, Fig. 14. The AII will anticipate attacks



by activating specialized agents seeking the presence of intruders into the network,

Fig. 14. Cybersecurity Holarchy

similar to how antibodies fight viruses in biological systems.

- Inter-Enterprise Level

At the highest level, the "Command Post" embeds the generic security policy for an organization, which takes care of the following tasks:
- Crisis Management
- Coordinating with other organizations/government agencies
- Lower level systems management
- Shared information with trusted organizations
- Specifies which sets of network parameters should be analyzed by each entity in the holarchy

In case of an unexpected attack, every command post in the security holarchy is alerted, triggering fighter agents that specialize in eliminating attackers.

- Intra-enterprise level

At this level managers control specified agents to analyze and correlate data collected by them, whereas at the lowest level, local agents monitor specified activities. Their main functions are:
- Understand network topology
- Analyze information given by Agents
- Make decisions depending on network topology and information given by other managers and their agents
- Coordinate the 'atomic' agents (e.g. scheduling their operations)
- Manage the 'atomic agents' knowledge base updates and mediate information exchange with the 'command post' (Fig. 14).

Manager agents interact with the 'atomic' agents by (Fig. 15):
- sending goals, derived from security policies;
- delegating specific functions of monitoring/detection and specifying the various domains to monitor;
- gathering particular information, such as: the suspicion level of a particular user, the list of events generated by a user, etc.;
- gathering relevant reports or analyses, and alarms.

- **Atomic agents level**

The basic agents have the 'mission' to determine an initial attack by analyzing low-level network events ('local sniffers'). For this they carry on the following functions:
- Real-time monitoring of network packets;
- Full IP de-fragmentation and upper protocol data reassembly;

- Provide immediate information analysis in original environment, at that very instant and catching additional local data that might be required;
- Delay / block network traffic/ isolate segment suspected of 'attack'
- Content inspection for security behavior violations
- Delete, modify suspicious/malicious content

The holonic approach enables also a topology-oriented approach in which critical points of action are identified where agents 'migrate' as needed. This enables in addition to the automatic detection of an attack, also attack localization as close as possible to its source. Agents must be able to isolate a specific network's segments. Managers coordinate the activity of basic agents by moving the basic agents across different network points in order to investigate what is the really "relevant" information and how to extract quality from quantity. For details of our system's implementation see [30].

6.8. Security-related challenges

- Can a trusted access capability be built into security protected environments, enabling emergency help (medical, fire brigade and police) to intervene when life-critical help is at stake?
- How can we decide on the appropriate policies, strategies, architectures and allocation of resources in the absence of an assumed rationale for threat?
- Across an open, large community, how can knowledge be securely exchanged over time, as the community evolves and data and trust change?
- How can we manage the security associated with spontaneous cooperation without imposed or predefined fixed roles and rules?
- Can the ideal of running secure applications on an insecure network be reached? Can we include liability in the design rationale?

6.9. Generic Challenges in Engineering Self-Organizing Applications

Some of the difficult questions posed by this research are:

- Can pathological emergent behavior of the total system, arising from the interactions between people, agents, objects, and their various policies, be avoided?
- How do we translate the interaction of agents in different contexts and environments into machine understandable language?
- How do we express and code sufficient real world semantics when the scope of interaction between agents is too broad or not predefined [35]?

There are many challenges in realizing AIIs. Highly interdisciplinary research (e.g., industrial engineering and control systems, distributed artificial intelligence and logic programming, information systems and communication technologies) is required to develop and implement dynamic services for a networked economy. We hope that the proposed research will succeed in tackling these complex developments with appropriate solutions emerging.

7. Conclusions

We propose a theoretical foundation for the design of adaptive information infrastructures (AIIs) enabling and sustaining tomorrow's e-Society, as well as envision various areas of industrial application for such AIIs, that would improve human life. The recent theoretical results obtained by us in modeling the property of emergence in self-organizing systems were refined and expanded with other recent results to create a model of *emergence in Cyberspace*, by this setting a foundation for engineering self-organizing applications mirroring biological behavior.

Embedding and intelligence are essential in our vision. Besides the physical embedding facilitated by miniaturizing and by reducing technology costs, as socially embedded information infrastructure AIIs are destined to become an integral part of our life by supporting, rather than disturbing, a framework that facilitates strategic partnerships among 'cyber-highway enabled' participants while providing greater user-friendliness, more efficient services support, user-empowerment, and support for human interactions. Intelligence can range from context-awareness, to more personalized and adaptive systems. In this vision, people will be immersed in such intelligent and intuitive infrastructures embedded in everyday objects in an environment recognizing and responding to the presence and needs of individuals in a seamless way.

The principal merit of the proposed holonic AII architecture is that it provides an environment that can react appropriately to highly unpredictable situations. By using natural models of emergence, much in the same manner as DNA is controlled in genetic engineering, we will be able to control the emergence of AIIs as crises arise. AIIs will address the emergency quickly, efficiently and most appropriately. Once a goal is set (where a certain need has to be fulfilled), the AII self-organizes to accomplish this goal optimally.

AIIs are applicable to a wide range of problems requiring timely configuration and coordination of distributed resources needed to address emergency situations, such as: *disaster emergency logistics* (evacuation planning, scheduling of emergency relief crews, food and water distribution, hospital bed planning); *national defense and security* (emergence of military AIIs as infrastructure for coordination of military operations in case of an unexpected attack);Cybersecurities (network and information securities); *ubiquitous ad-hoc healthcare* (emergence of medical AIIs grouping the most suitable medical entities able to cooperate and organize their interaction to respond adequately to patient's need; medical emergency logistics with patient information retrieval and heterogeneous transaction workflow management throughout the medical organization); *fault-tolerant flexible production* (emergent planning and scheduling of reconfigurable manufacturing production; customer-centric supply chain and workflow management; fault tracking and error reporting across the manufacturing organization).

Our future work will focus on the design of a reference model that enables the quick deployment of AIIs for emergency applications. We will expand our previous results on global production integration, to other manufacturing areas, such as continuous monitoring of various processes and pipelines to predict changes in delivery schedules or unanticipated maintenance of equipment. We will investigate new areas of application, such as: how the AII approach could help prevent communication network outages by agent monitoring of network traffic on various routers or how can it be used to provide advance warning of an impending health epidemic (e.g. bird flu, SARS) based on simultaneous agent monitoring of multiple hospital emergency room activity.

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