Pre-print version
M. Calabrese, A. Amato, V. Di Lecce, V. Piuri, "Hierarchical-granularity holonic modelling", in Journal of Ambient Intelligence and Humanized Computing, Springer, September, 2010. ISSN: 1868-5137. [DOI: 10.1007/s12652-010-0013-3]

Hierarchical-granularity holonic modelling

Marco Calabrese · Alberto Amato · Vincenzo Di Lecce · Vincenzo Piuri

Abstract Design criteria for distributed and pervasive intelligent systems, such as Multi Agent Systems (MAS), are generally led by the functional decomposition of the given application-dependent knowledge. Consequently, changes either in the problem semantics or in the granularity level description may have a significant impact on the overall system re-engineering process. In order to tackle better these issues, a novel framework called Hierarchical-Granularity Holonic Model (HGHM) is introduced as a holon-based approach to distributed intelligent systems modelling. A holon is an agent endowed with special features. Seen from the outside, a holon behaves like an intelligent agent; seen from the inside, it appears to be decomposable into other holons. This property allows for modelling complex distributed systems at multiple hierarchical-granularity levels by exploiting the different abstraction layers at which the design process is carried out. The major benefit of the proposed approach against traditional holonic systems and MAS is that the entire HGHM-based architecture can be derived directly from the problem ontology as a hierarchical composition of self-similar, modular blocks. This helps designers focussing more on knowledge representation at different granularity levels which is a very basic process, as in top–down problem decomposition. Starting from the literature on holonic systems, a theoretical model of HGHM is introduced and an architectural model is derived accordingly. Finally, a customized application for the case study of distributed indoor air quality monitoring systems is commented and improvements in terms of system design with respect to well-established solutions are considered.

Keywords Hierarchical-granularity holonic model · Multi Agent Systems · Knowledge-based approach

1 Introduction

The implementation of wide and dense sensor networks able to monitor various parameters, such as the air quality in environmental applications, is nowadays feasible even with off-the-shelf technologies. Since these networks are generally composed of many low-cost nodes, they allow for monitoring wide areas with a high level of spatial detail. On the other hand, they acquire a huge quantity of data, thus requiring ever more advanced approaches to be handled (Abilemona et al. 2010). Another specific aspect of these sensor networks is the significance of the sampled data. Indeed, data sampled by a given node can be considered as detailed observations of a local phenomenon. The integrated analysis of data simultaneously sampled by various neighbourhood nodes gives information about a phenomenon interesting a wider area. Working on the dimension of the neighbourhood, it is possible to have a telescopic vision of the observed phenomenon by changing the observation scale. This requires however flexible and scalable architectures endowed with sufficient autonomous intelligence in order to solve specific problems without human intervention.

The effort to minimize the semantic distance between smart devices and the final human user is a major point of concern (Acampora and Loia 2008). In fact, employing a large amount of low-cost general-purpose devices puts forth the need for managing local intelligence in an effective and efficient way. This problem is being addressed since almost two decades by scholars in the field of Artificial Intelligence such as in Wooldridge and Jennings (1995), giving rise to the concepts of agents and MAS.

The definition of *what* an agent actually is seems to be a source of deep controversy. According to a groundwork survey on Artificial Intelligence (Russell and Norvig 2002) two main approaches can be identified in the agent literature. They focus, respectively, on the reasoning aspects (rationalistic view) and on the behavioural aspects (behaviourist view). The synthesis of the two positions is represented by the rationale agent where the paradigm of correct inference is left apart in favour of a more pragmatic approach that accepts sub-optimal choices.

Fostered by a rapid advance in hardware and software technologies and by the increasing need for the management of complex distributed systems, the attention of researchers has progressively moved the focus on agent organizations, namely Multi Agent Systems (MAS). In the latest years, MAS-based approaches have spawned a countless variety of engineering applications. Nevertheless, the search for a shared theoretical model for MAS has produced a long debate in the research community (Flores-Mendez 1999).

Although MAS provide potential advantages in the field of distributed systems, a number of challenges arise in their design and implementation (Sycara 1998). Namely, the most important are: problem decomposition, agent communication, decision making, global coordination, technology issues. In Di Lecce et al. (2005) a MAS layered architecture facing these points was introduced. The architecture is based on three layers: interface, broker/coach and validation. These layers represent the functional steps needed in the information processing flow driven by the knowledge-based design process. The main critical aspect of this architecture is its dependence on the context knowledge granularity. If a more analytical knowledge description is provided, this requires rewriting the architectural design process. To overcome this limit, our investigation is moved towards holonic-based architectures.

In the late 1960s, Koestler (Koestler 1971) introduced the concept of 'holon' as an entity being simultaneously a whole and a part of a whole. The idea was taken by comparison with the biological world where multiple entities participate at different granularities to the goal of the living creature which host them. Since then, several holonic-based systems have been presented in the literature, especially in the last decade (Adam et al. 2000; Fletcher et al. 2000; Kremer and Norrie 2000; Fujita 2001; Cheng et al. 2001; Fleetwood et al. 2003).

From an engineering perspective, it is noteworthy that a holon behaves as an intelligent agent at the interface level and, at the same time, is decomposable into other holons from the inside. This property makes holon a suitable conceptual model for handling different granularity levels. Consequently, the search for modular, autonomous, and cooperative building blocks to employ in the management of complex systems has fostered the idea of holonic modelling approaches (Clegg 2007). This trend is particularly evident in the field of Intelligent Manufactory Systems with the so-called Holonic Manufacturing Systems (HMS).

Due to this genesis, holonic systems have caught the interest of researchers around the architectural issues at an enterprise level. In Simão and Stadzisz (2009) for example a rule-based interpretation of an HMS for simulating process-driven and product-driven control is proposed. However, real world implementations of HMS are still few (Tichy et al. 2005; Leitão and Restivo 2008) while comprehensive theories involving concepts like emerging intelligence have been published only in recent times (Ulieru and Este 2004).

In this work, a holonic model named 'Hierarchical-Granularity Holonic Model' (from now on referred with the acronym HGHM) is presented as a knowledge-based architectural solution for a number of applications at an enterprise level. The major benefit of the proposed approach against traditional holonic systems and MAS is that the entire HGHM-based architecture can be derived directly from the problem ontology as a hierarchical composition of self-similar, modular blocks, that scale up design performances. The basic idea is that system knowledge can be handled at different levels of abstraction and related granularity, emerging from the problem context towards the user application layer. In order to test the efficacy of our approach a HGHM-based indoor environmental monitoring system will be discussed in detail.

The structure of the paper is as follows: Sect. 2 reports related work on holonic models and their relationship with MAS; Sect. 3 shows the main characteristics of the proposed HGHM-based architecture; Sect. 4 describes the used system design; a case study is presented is Sect. 5; conclusions and final remarks are drawn in Sect. 6.

2 Related work

In the framework of systems engineering, the role of holon-based modelling is gaining more and more consideration because it allows for systems (and subsystems) thinking from a novel (wholly comprehensive) perspective.

In a work published in 1998 (Thompson and Hughes 1998) the holonic paradigm was presented as a suitable theoretical model to describe (human and computer) activities within a given organization. The work was led by the aim of finding an improved solution to the design of computer integrated manufacturing systems. The basic building block characterizing the holon formal description was adapted from the object-oriented notation to represent IT support of a business process at the top level.

It is noteworthy that, the object-oriented formalism is generally used also as a description of intelligent agents (Van Dyke Parunak and Odell 2002). This poses the question of understanding which differences exist between the two conceptual models.

A first comparison between holon and agent was presented in Giret and Botti (2004) where a comprehensive confrontation was carried out. Three interesting points are:

- Information and physical processing: both elements are present in holons while agents are generally considered only as software entities;
- Recursiveness: which is characteristic for holons but not for agents;
- Organization: holons organize themselves according to holarchies, generally represented as dynamic hierarchic structures (Xiaokun and Norrie 1999), while agent architectures are fixed and can range from horizontal to vertical organizations (Sycara 1998; Okamoto et al. 2008).

All previous points mark the difference about architectural properties, distinguishing holon from its agent counterpart.

2.1 Information and physical processing

As for information and physical processing are concerned, the commonly accepted architecture to take as a source of inspiration is the one proposed in Christensen (1994) and reported in Fig. 1. The interesting behind this representation is that holon is an indivisible composition of HW and SW, along with its functional constituent layers. It is

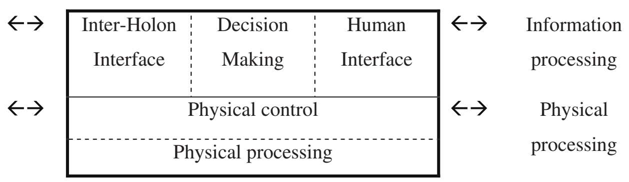


Fig. 1 Multi-layer intra-holon architecture according to Christensen (1994)

therefore impressive how this three-layered architecture can be mapped onto the three levels (bare machine, firmware and operating system) of a multi-level Von Neumann architecture (Tannenbaum 2006) equipped with Operating System (OS). A similar three-partition can be also found in other works (Colombo et al. 2006) in the field of Intelligent manufacturing Systems.

In Fletcher and Deen (2001) functional blocks are proposed to manage real-time control for low-level process-machine interaction. In the authors' view, each autonomous holon is composed of a hierarchy of large-grain functional components where interaction is carried out by user-defined cooperation strategies. It is useful mentioning that the authors apply IEC 61499 as a standard-based implementation of their model.

In industrial process management and control systems, function blocks are considered to be computational elements (Fig. 2a) of distributed application in a decentralized control system (Fig. 2b). Since applications map into devices over the communication network, any application model can be viewed as the composition of event-driven functional blocks exchanging data to manage process control (Fig. 2c). A more detailed overview on IEC 61499 can be found in Christensen (2007).

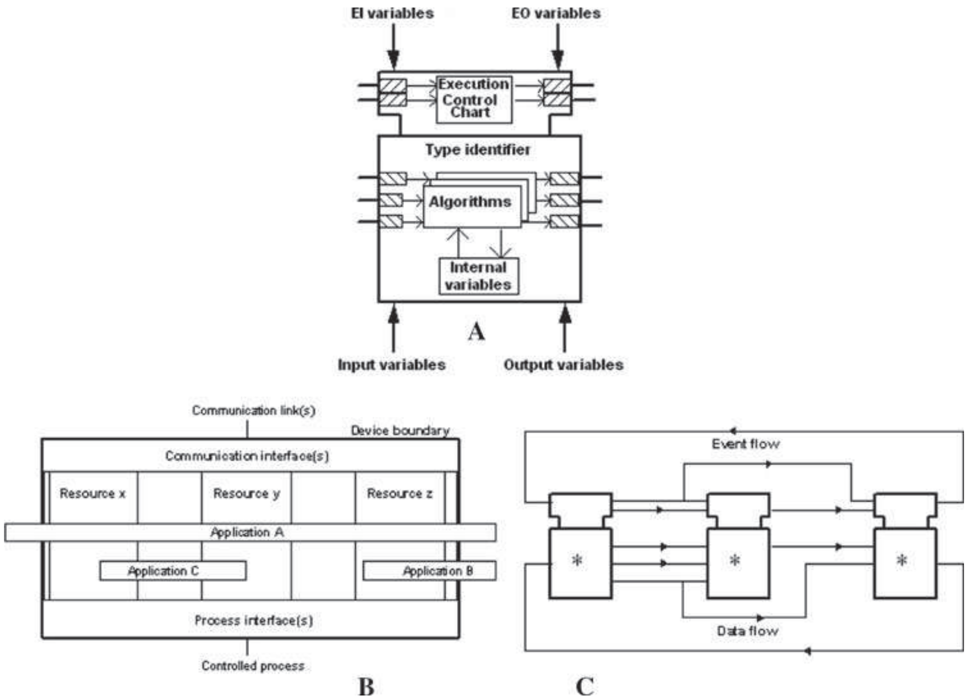
2.2 Recursiveness

Recursiveness is a special property of a function to call itself in a nested fashion; therefore it is evident that in order for a recursive function to be properly executed, an OS layer is necessary to handle the stack of nested calls. From the point of view of recursiveness, any (decomposable) holon can be described by a recursive agency according to the model presented in 2002 (Van Dyke Parunak and Odell 2002). The authors extend the Unified Modelling Language to support the distinctive requirements of MAS through an object-based description. They state: "…*agent systems are a specialization of object-based systems, in which individual objects have their own threads of control and their own goals or sense of purpose*". The holonic (recursive) object-based representation is depicted in Fig. 3; with minor adaptations, it is confirmed by recent works concerning HMS (Walker et al. 2005). With reference to Fig. 3, every MAS is made of a collection of agents and is an agent itself; the atomic agent corresponds to an agent that cannot be decomposed (hence it is not a MAS).

2.3 Organization

Holarchy is a specific organization of holons. Theoretically, any (MAS) holon could be described recursively by a holarchy until the desired granularity level description is reached. For these reasons, when referring to a holarchy,

Fig. 2 IEC 61499 standard. Three basic views are displayed: function block (**a**), system model (**b**), application model (**c**)



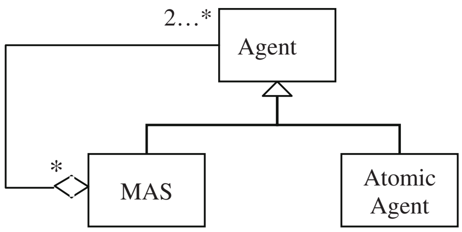


Fig. 3 Agent recursive architecture adapted from Van Dyke Parunak and Odell (2002)

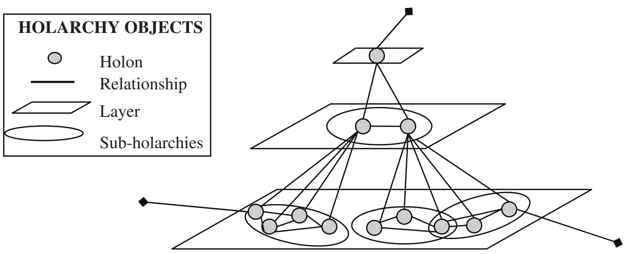


Fig. 4 Holarchy layered architecture expressed in a graph-based notation. *Holons* correspond to nodes, while *relationships* correspond to edges. Holons groups into small clusters (*sub-holarchies*) at each layer. External relationships allows the holarchy for communicating with the external world

the generally accepted abstract underlying structure is a hierarchical aggregation of holons like the one in Fig. 4.

Some authors (Shafaei and Aghaee 2008) attempt to provide a behavioural description of the holarchy. They assume that, for an external observer, those simple and reactive acts take place at the base of the holarchy while complex activities and behaviours are observable at the top of the holarchy. In other words, lower levels are more reactive and upper level holons are more proactive. It is useful noticing that this layered viewpoint is the same described in Sycara (1998) to MAS.

In Simão et al. (2009), a classification of system architecture approaches is framed according to both theoretical and modelling aspects (Table 1). The authors identify holonic thinking as an extension of ontology-based theories. This can be considered an evolution of the heterarchical approaches to adaptable and agile systems. Furthermore, the authors consider MAS to be the natural implementation of holonic modelling. Under this perspective MAS technologies represent an efficient tool to support holonic-based systems design, provided that ontology paradigm is revised according to a holistic representation.

Contrarily to hierarchical MAS where agent position is determined by its role (driven by functional system decomposition during the design process), holons assemble into a holarchy depending on the ‘knowledge flow’ that, at any level, is necessary to accomplish the system goal. Put this way, knowledge ‘emerges’ from the context and is processed throughout the holarchy in order to achieve the common goal.

The principle of emerging knowledge has been formally postulated in Ulieru and Este (2004) with the intent of describing holarchy as a coordinated system aiming at minimizing system entropy. The authors explicit that optimal knowledge at the holarchy highest level of resolution

Table 1 Hierarchy of systems architectures (Simão et al. 2009)

Approach		Paradigms	
		Theoretical	Modelling
5	Adaptable or agile	Fractals, bionics, and holonics	Muti Agent Systems (MAS)
4	Heterarchical or interoperable	Ontologies and cognitics	Uncoupled system (objects/agents)
3	Hierarchical integrated or visible	Systemics and system eng.	Computer integrated manufacturing (CIM)
2	Hierarchical or rigid	System theory	Automatic control
1	Isolated or fragmented	Empiricism	Ad hoc approaches

(inter-enterprise level) corresponds to an optimal level of information organization and distribution among the agents within all levels of the holarchy. Moreover they use entropy as a measure of the degree of order in the information spread across the multi-agent system modelling the holarchy.

Our work complies with this knowledge-based interpretation. Furthermore, an attempt is made towards a better definition of the architectural aspects that are close to this viewpoint. An example implementation that analyzes the context of indoor monitoring will be described further in the text.

3 Proposed system overview

The core of the proposed HGHM is that knowledge specific to the problem context is handled at hierarchical granularity levels. This behaviour reflects in the holarchy structure: the more the holarchy grows far from the context, the more wide-concept covering the type of information processed and obtained. Since the designer chooses the desired level of abstraction, the architecture can be extended or reduced in a telescopic fashion.

In order to provide a more formal representation of HGHM properties, some formal definitions are introduced in the following.

3.1 Def. holonic components

Let $H = \{L_1, L_2, \ldots, L_n\}$ be a collection of holonic layers composing the hierarchical framework where each layer $L_i = \left\{h^i_1, h^i_2, \ldots, h^i_{n_i}\right\}$ contains a collection of n_i holons; let $S = \{s_1, s_2, \ldots, s_t\}$ be a set of environmental sensors connected to H and let $A = \{a_1, a_2, \ldots, a_r\}$ be a collection of actuators settable by holons in L_i with $i = 1,\ldots,n$.

3.2 Def. holonic hierarchy and communications

In order to formally introduce the communication constraints in our hierarchical holonic architecture, a binary relation $<^R$ is defined on the set $H = \bigcup_{i=1}^n L_i$, if the following holds:

1. $h^p_l <^R h^p_q$ iff $q = p$ or $q = p + 1$, with $p = 1\ldots n_i$
2. $s <^R h^p_l$ if $s \in S$ and $p = 1$
3. $h^p_l <^R a$ if $a \in A$ and $p = 1,\ldots,n_i$

In other words, the relation $<^R$ defines the holonic communication constraints by means of the following subsets:

$C_H = \{ \left(h^p_l, h^q_k\right) \in <^R | l = 1\ldots n_p, k = 1\ldots n_q, p = q = q+1$ and there exists a communication channel between h^p_l and $h^q_k\}$. With reference to the pair $\left(h^p_l, h^q_k\right)$, if $q = p$ then the channel is named intra-level channel, otherwise it is named inter-level channel.

3.3 Def. holonic semantic view

The hierarchical holonic system semantic view defines how each layer in H can be contextualized to a given application domain. In more detail, let $O = \{o_1, o_2, \ldots, o_n\}$ be a collection of ontologies that models a set of sub-contexts related to a composed application domain, then $f : \bigcup_{i=1}^n L_i \to O$ is a function such that $f\left(h^p_l\right) = o_q$ iff $p = q$.

All previous definitions provided, it is possible to define HGHM this way:

3.4 Def. hierarchical-granularity holonic model

An HGHM is any tuple of the following type:

$$\text{HGHM} = \left\langle H, S, A, <^R, O, f \right\rangle$$

It is noteworthy that the proposed HGHM, as formally described above, is conceived as an ontology-based architectural solution for handling knowledge at an enterprise level compliant with the layered view of Fig. 4. As long as the holarchy emerges from the context towards higher abstraction levels, it grounds on physical data coming from the environmental sensors.

The basic consideration behind the HGHM is that, given a complex distributed system (like most pervasive monitoring applications), the use of locally distributed smart devices is not sufficient to guarantee an effective and efficient management alone. The amount of information that comes from scattered sources, actually representing different observation points of the same macro-phenomenon, needs to pass through a number of phases (i.e., pre-processing, validation, elaboration, fusion etc.). Traditional MAS approaches would face this issue by imposing an agent organization that fixedly assigns a functional role to each agent: the main drawback is the stiffness of the whole system. In this case, in fact, MAS architecture is built in consequence of a thorough inspection of the underlying ontology.

The term 'ontology' signifies the set of conceptualizations (Gruber 1995) describing the problem domain by means of a given representational vocabulary. Moving from metaphysics, the modern interpretation of 'ontology' attempts to deal formally with knowledge representation under the new light of computer science. Ontology can be considered as a pragmatic expression of Knowledge Representation.

In Davis et al. (1993) the authors pointed out that, at that time, the question about what Knowledge Representation actually is still had not been answered directly. Since then, a great effort has been engaged by scholars in different research fields. Significant outcomes were obtained in the field of psycholinguistics with the setup of electronic databases like WordNet (Fellbaum 1998). Among several applications, WordNet has been employed with promising results in the Semantic Web (Berners-Lee et al. 2001), especially for automatic sense (i.e. context) disambiguation (Navigli and Velardi 2005; Di Lecce et al. 2009b, c).

Knowledge is often represented according to hierarchical (not looping) data structures such as trees or directed acyclic graphs (DAGs) where nodes represent concepts and arcs account for lexical or semantic relations. This happens for example in the WordNet IS-A taxonomy (Fellbaum 1998). A so formed hierarchical dataset can be sliced at different levels with cuts occurring at the same distance from the root. By convention, the root (most general concept) is at the top of the hierarchy, while more specific concepts span toward leaves. Each level aggregates concepts with similar granularity: these levels can be themselves clustered according to their sub-contexts, actually defining sub-ontologies organized in the form of holarchies as in Fig. 4.

In the HGHM-based holarchy, all the holons at the same level (representing one or more sub-holarchies) share the same ontology. The holons at the lowest level receive data from the real world using a set of sensors. Furthermore, these holons can handle various actuators to operate in the real world. All the holons at the higher levels receive data only from the holons at the neighbouring lower level. Each holon can communicate with other holons at its same level

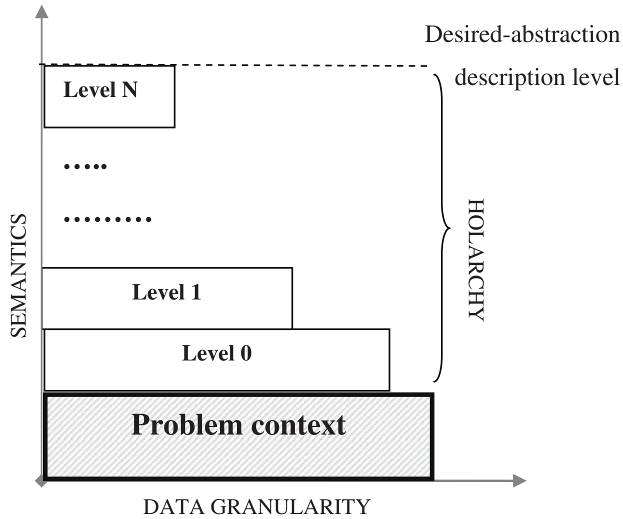


Fig. 5 Proposed HGHM-based multi-level holarchy. Holarchy is layered into levels according to increasing semantics and decreasing data granularity until a desired description level is reached

or with a holon at the neighbouring higher level. The relationship between the holons at a given level and the holons at the neighbouring lower level is a one-to-many relationship.

Using this approach, by rising from a level to another of the holarchy, it is possible to synthesize concepts. In other words, the proposed system is able to give a telescopic vision of the model under analysis. Each level gives a specific level of detail about the observed system. A figurative description of the HGHM is depicted in Fig. 5.

4 HGHM-based system design

In this section, the architectural aspects deriving from the previously described HGHM-based holarchy are presented.

Figure 6 depicts a schematic representation of the component-based architecture. As this figure shows, the system is decomposed into as many components as there are levels in the holarchy. Each component is an autonomous sub-holarchy which can be characterized by one ore more holons working in cooperation. Inter-level communication is handled through a bus line. Data throughput of lower-level components is generally high with a low semantic content, while the vice versa holds for upper-level components. The semantic level of the managed information grows up rising among the components while the level of detail about the problem context has an opposite behaviour.

The number of used level components (equal to the number of levels in the holarchy) varies according to the requirements of the specific application. For example, in the next section, an HGHM composed of three layers is

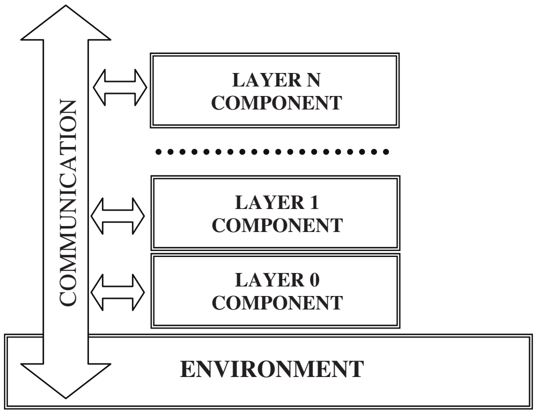


Fig. 6 Component-based view of the proposed HGHM

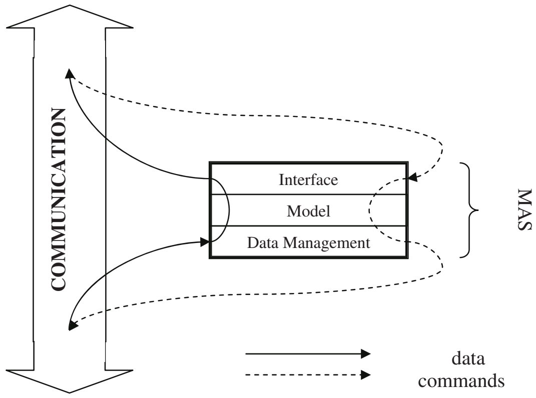


Fig. 7 Component-based architecture at a generic level. The component block handles data processing and command execution through a hierarchical MAS

applied to modelling a distributed sensor network used in air quality monitoring.

The key element of the system is the modular component that is represented by a rectangle in the schema in Fig. 6.

The main tasks of this component block are:

- Receiving data: according to its level in the holarchy, each block can receive data from real world sensors (layer 0 component) or from other blocks at a neighbouring lower level;
- Modelling: each block is able to process incoming data flow through one or more models. Output data is then an input for the neighbouring upper component;
- Setting actuators: in order to perform actions in the environment, each block is able to send control commands to actuators that logically pertain to its ontological layer;
- Communication: according to its level in the holarchy, each block is able to communicate with other blocks or with real world actuators.

4.1 MAS design

According to previous theoretical considerations, each component block can be designed inside as a MAS (Fig. 7). The layered MAS architecture presented in Di Lecce et al. (2005) is here employed. It consists in three main functional layers:

- Data management: each MAS is able to receive data from MAS standing at a level lower than its own. These data are processed in order to verify: their quality in terms of consistence with the holarchy level and their suitability for the holon model;
- Model: each MAS is able to compute one or more models that, working on input data, infer information at a higher semantic level; the outputs of the model determine the state of the holarchy. There is a set of possible states defined according to the specific modelled system. Each MAS can have a single state at time;
- Interface: this part handles all the aspects of the communication for each MAS. The main tasks of this module are:
  - Translating the MAS state into communicable events. These events can be communicated to other MAS at the same level or at the neighbouring upper level. Each MAS has the ability to communicate with the user.
  - Receiving commands by the MAS at the neighbouring upper level. These commands are interpreted according to the level's ontology. These commands can modify the behaviour of the MAS or they can be translated into commands for the lower layer (namely into commands for other MAS or for a set of actuators).

This structure is replicated for each component block in the system. It is useful to notice that human users can be viewed as a further component atop of the layered architecture.

4.2 Communication aspects

In compliance with Fig. 7, information flow traverses the HGHM-based architecture following two opposite directions: upward and downward. The upward flow accounts for data raising towards higher layer components; the downward flow triggers commands directed towards actuators or lower layer components. Both commands and data communications are implemented, by default, through asynchronous message exchange for at least reasons of two orders:

1) since HGHM is ultimately conceived for human-centric applications, user requests can occur at any time. In this sense, the architecture must be as flexible as to balance appropriately heavy load requests with real-time constraints.
2) data require time to be processed. After processing, it can happen that the processed output is considered irrelevant with respect to the local ontological model and does not produce a data communication act to the upper layer. From this perspective, HGHM is more suited to event-driven programming, a technique that is experiencing an increasing interest in modern software engineering due to the ability of handling multi-level abstraction coding more straightforwardly than traditional programming techniques (Meyer 2009).

Both the two previous points are compatible with well-known communication standards such as Agent Communication Language (ACL) and related Java-based implementations like the Java Agent Development Framework (JADE) (Bellifemine et al. 2007). Similarly, it is useful to mention that agent-sensors or agent-actuators communications based on the eXtensible Markup Language (XML) have also been proposed in recent years (Acampora and Loia 2005) and can be applied straightforwardly in HGHM settings as well.

5 HGHM-based applications: a case study overview

To supply more technical clues in the implementation of the provided model, an HGHM-based application in the field of distributed air quality monitoring systems are discussed.

The first studies about the air pollution, undertaken by industry, started in the 1950s. In various countries, the obtained results allowed the introduction of specific laws to protect the environment and consequently the human health. The air quality analysis was extended to indoor environments later, when, in the 1970s, there were some cases of pulmonary diseases into air-conditioned buildings. The air quality monitoring for indoor environments is becoming an interesting issue in the most economically developed countries. Indeed, in these countries people show strong tendency to spend their time in indoor environments. According to (Bocchio and Masoero 1992) in these nations people spend till the 90% of their time in indoor environments, 30–40% of this time is spent in working environments. Starting from these data, it appears clear how the necessity of new monitoring systems designed to work in various indoor and outdoor environments is extremely relevant.

The latest improvements both in the field of sensors and in ICT technology are opening the way to the development of innovative pervasive distributed sensor networks composed of many low-cost nodes. In Di Lecce et al. (2009a) the nodes are composed of two main modules as shown in Fig. 8. The sensors module is made up of a set of analogical sensors whose number and type vary according to the application. The processing module is based on a programmable unit handling various aspects of the acquisition and data management process (sampling, compressing, sending and, possibly, setting actuators). A key element of these nodes is their ability to send data through a network using various connections (such as wired and wireless network, GPRS and UMTS) according to the specific application. These processing units are characterized by reduced size and good computational power allowing them to execute complex tasks.

Typical examples of indoor air quality monitoring applications are big civilian buildings and industrial environments. These environments are composed of various areas characterized by strong micro-climatic heterogeneities (i.e. different rooms, area around different machineries, etc.). In these conditions the proposed holonic monitoring system, based on a dense sensor network, is able to analyze each micro-climatic area. On the other hand, the proposed architecture allows for changing the observation scale in order to have various levels of detail about the monitored environment.

5.1 Proposed architecture in more detail

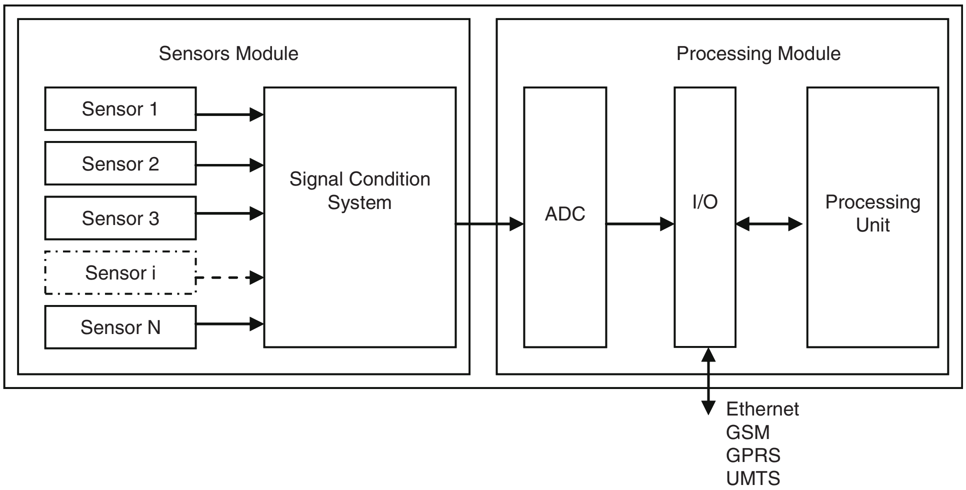
One of the advantages of the HGHM-based architecture is that it is possible to add as many levels as one wants without changing the modular structure depicted in Fig. 6;

Here it follows a more detailed description for each layer.

L1. The lowest level is composed of all the sensors in the network. Here information is local, namely, it is referred to specific monitored location. The main tasks of the holons at this level are:

- Sampling data: each holon samples data at a given sampling rate according to the specific application;
- Data validation: each holon implements various validation algorithms in order to avoid the well known problem of incomplete data series (Di Lecce et al. 2008) These algorithms work only on local sampled data;
- User interface: each holon at this level has a simple web based user interface. Using this interface a user can have local information about the monitored environment.

Fig. 8 A schematic overview of the proposed acquisition system



L2. The second level of the architecture works at a higher semantic level. Here the monitored building is considered as divided in various regions. A region is composed of several neighbouring locations (i.e. a set of neighbouring rooms). In the proposed HGHM-based architecture, at this level there is one holon for each region. Here each holon:

- Works with several neighbouring holons standing in the previous level;
- Handles information referred to a whole region of the monitored environment. The size of this region is in inverse proportion to the heterogeneity level among the various areas of the monitored environment.

At this level, each holon has the following tasks:

- Area modelling: for each monitored region, a holon builds a model about the daily evolution of the monitored parameters. This model plays a significant role in the next task;
- Spatial validation: this is a further level of validation implemented in this system. Data sampled from various nodes are compared among them. When a significant discordance is found between two or more nodes (namely between two ore more neighbouring monitored areas), the sampled data are compared to those computed by the model. If the actual situation is compatible with the model then data are labelled with a high reliability coefficient else the reliability coefficient is reduced (proportionally to the divergence);
- Alarm management: when critical conditions are detected, the system is able to raise various levels of alarm, according to the criticality of the event. Using area modelling and spatial validation, it is possible to infer if a given situation is due to a sporadic local event or to a phenomenon that is interesting a wider area;
- User interface: at this level, user can obtain qualitative and quantitative information about the trend of the various monitored parameters. The interface shows average information about the whole region. When a local critical condition is detected the interface passes the control to the holon at the lower level in order to show local detailed data about the event under analysis.

L3. The third level of the HGHM architecture implements the same functions of the second layer but working at a higher level. Indeed, here the holon works on the features extracted by the holons at the second level. Here the area-modelling task is referred to the entire monitored structure. The alarm management function is used to handle critical events involving more than one regions of the monitored structure. Likewise, the user interface shows the same kind of information but referred to the whole monitored environment.

5.2 Advantages in HGHM-based architectures

The proposed HGHM architecture overcomes the MAS architectures in terms of scalability and flexibility. MAS architectures have been widely used in sensor network applications (Biswas 2005; Dai et al. 2008, etc.) due to their ability in modelling and analysing sensor data up to their complex fusion. These architectures are characterized by a layered structure. The semantic level of information grows up from the lower to the higher layer of the MAS.

An interesting example of such layered architecture is in Biswas (2005). In this work the author proposes a three layers architecture to manage a sensor network. The three layers are: application layer, service layer and data layer. The application layer supports interoperable agent-based applications. These applications involve software agents interacting locally or remotely to accomplish their tasks. The distributed service layer integrates the sensor network application with the sensor nodes. It provides a large number of services designed for the specific application (e.g.: services for communication, mobility, management, security, clustering, fault-tolerance, etc.). The data layer consists of the distributed sensor nodes, where each node acts as a source of the data that is collected from its sensors. This system defines a Region Management Station (RMS) middleware coordinating the integration of the sensor nodes of a region with the rest of the network. This system is very flexible, indeed; by changing or adding different agents at the application layer, it is possible to satisfy other requirements of the users. Furthermore, it has a good level of scalability because it is possible to add other sensors and regions adding a RMS and the required agents.

The limit of this kind of architectures is that they have a single level (or a prefixed number of levels defined at design time) of data aggregation (i.e. the RMS module in the given example). The proposed HGHM architecture overcomes this limit because it is possible to modify the level of data aggregation adding one or more levels to the Hierarchical-Granularity Holonic model without modifying the other levels.

6 Conclusions

In this work, the Hierarchical-Granularity Holonic Model has been introduced. It supplies a knowledge-based holistic solution to the problem of handling complex systems at different semantics granularity levels, thus overcoming the MAS architectures where the system is decomposed according to functional hierarchies. The idea that drives the holarchy building process is that system knowledge can be handled at different granularities. This makes HGHM holarchy emerging from the problem context towards higher levels of abstraction until a desired level of description is reached. System design is performed through block decomposition according to levels defined in the holarchy formation phase. Moving from sensor data, information processing flows through layered components in bottom-up direction, while state control moves downward. A hierarchic MAS has been employed for managing information in each component-block. This approach is in line with recent rends on holonic modelling, characterizing holon-based systems by their emerging intelligent behaviours and their implementation through MAS-based techniques. The novelty grounds on the fact that a comprehensive knowledge-based approach (both theoretical and practical) has never been presented so far in the literature of holonic systems.

HGHM-based modelling is a complete and fully general approach with respect to the chosen application contexts. In order to provide an inclusive overview of the proposed approach and highlight its benefits in terms of scalability and design performances, an HGHM-based indoor environmental monitoring system design has been described as case study.

Acknowledgments The authors would like to thank the anonymous reviewers whose proposals and comments helped us improve the overall paper quality.

References

Abilemona R, Petriu EM, Whalen TE (2010) Distributed intelligent sensor agent system for environment mapping. J Ambient Intell Hum Comput 1(2):95–110. doi:10.1007/s12652-010-0010-6

Acampora G, Loia V (2005) Fuzzy control interoperability and scalability for adaptive domotic framework. IEEE Trans Ind Inform 1(2):97–111

Acampora G, Loia V (2008) A proposal of ubiquitous fuzzy computing for ambient intelligence. Inf Sci Int J 178(3):631–646

Adam E, Mandiau R, Kolski C (2000) HOMASCOW: a holonic multi-agent system for cooperative work. In: Proceedings of the 11th international workshop on database and expert systems applications, pp 247–253

Bellifemine F, Poggi A, Rimassa G (2001) Developing multi-agent systems with JADE, Lecture notes in computer science. Springer, Berlin, pp 42–47

Berners-Lee T, Hendler J, Lassila O (2001) The Semantic Web, Scientific American, pp 29–37

Biswas PK (2005) Architecting multi-agent systems with distributed sensor networks. In: Proceedings of KIMAS 2005, Waltham, MA, USA, pp 161–166, 18–21 April 2005

Bocchio V, Masoero M (1992) CH4, Energia, Metano, 2:15–20

Cheng TT, Yang HC, Lin JY, Hung MH (2001) The development of holonic information coordination systems with security considerations and error-recovery capabilities. Proc IEEE Conf Robot Autom 2:1832–1838

Christensen JH (1994) Holonic manufacturing systems: initial architecture and standards directions. In: Proceedings of the 1st Euro workshop on holonic manufacturing systems, HMS Consortium, Hannover, Germany, 1 December 1994

Christensen JH (2007) IEC 61499: a standardized architecture for adding value in industrial automation. In: Kitara seminar, HTC High Tech Center. Available at www.holobloc.com

Clegg BT (2007) Building a holarchy using business process-oriented holonic (PrOH) modelling. IEEE Trans Syst Man Cybern Part A Syst Hum 37(1):23–40

Colombo AW, Schoop R, Neubert R (2006) An agent-based intelligent control platform for industrial holonic manufacturing systems. IEEE Trans Ind Electron 53(1):322–337

Dai Z, Sun B, Wang H, Li Y (2008) A three-layer cooperative knowledge modeling of multi-agent conflict system based on healthcare sensor decision network. In: Proceedings of 2008 international symposium on knowledge acquisition and modeling, pp 157–160

Davis R, Shrobe H, Szolovits P (1993) What is a knowledge representation? AI Mag 14(1):17–33

Di Lecce V, Amato A, Pasquale C, Piuri V (2005) Web agents in an environmental monitoring system. In: IEEE international conference on computational intelligence for measurement systems, Giardini Naxos, Italy, pp 262–265

Di Lecce V, Amato A, Calabrese M (2008) Decision trees in time series reconstruction problems. In: IEEE International instrumentation and measurement technology conference, Vancouver, Canada, pp 895–899, 12–15 May 2008

Di Lecce V, Calabrese M, Piuri V (2009a) An ontology-based approach to human telepresence. In: IEEE conference on computational intelligence for measurement systems and applications, Hong Kong, China, pp 56–61, 11–13 May 2009

Di Lecce V, Calabrese M, Soldo D (2009b) Fingerprinting lexical contexts over the Web. J Univers Comput Sci 15(4):805–825

Di Lecce V, Calabrese M, Soldo D (2009c) A semantic lexicon-based approach for sense disambiguation and its WWW application. In: Proceedings of the ICIC 2008 conference, published in Lecture Notes in Computer Science, vol 5755. Springer, Berlin, pp 468–477

Fellbaum C (1998) WordNet. An electronic lexical database. MIT Press, Cambridge, MA

Fleetwood M, Kotak DB, Shaohong Wu Tamoto H (2003) Holonic system architecture for scalable infrastructures. Proc IEEE Int Conf Syst Man Cybern 2:1469–1474

Fletcher M, Deen SM (2001) Fault-tolerant holonic manufacturing systems, concurrency and computation: practice and experience. Special Issue High Perform Agent Syst 13(1):43–70

Fletcher M, Garcia-Herreros E, Christensen JH, Deen SM, Mittmann R (2000) An open architecture for holonic cooperation and autonomy. In: Proceedings of the 11th international workshop on database and expert systems applications, pp 224–230

Flores-Mendez RA (1999) Towards a standardization of multi-agent system framework. Crossroads 5(2):18–24

Fujita N (2001) Holonic controller and assembly task planning. In: Proceedings of the IEEE international symposium on assembly and task planning, pp 67–72

Giret A, Botti V (2004) Holons and agents. J Intell Manuf 15:645–659

Gruber TR (1995) Toward principles for the design of ontologies used for knowledge sharinge. Int J Hum Comput Stud 43:907–928

Koestler A (1971) The ghost in the machine. Arkana Books, Carneige-Mellon University

Kremer R, Norrie D (2000) Architecture and design of a holonic visual interface. Proc IEEE Conf Syst Man Cybern 3:1715–1720

Leitão P, Restivo F (2008) Implementation of a holonic control system in a flexible manufacturing system. IEEE Trans Syst Man Cybern Part C 38(5):699–709

Meyer B (2009) Touch of class: learning to program well with object and contracts, Springer

Navigli R, Velardi P (2005) Structural semantic interconnections: a knowledge-based approach to word sense disambiguation. IEEE Trans Patter Anal Mach Intell 27(7):1075–1086

Okamoto S, Scerri P, Sycara K (2008), The impact of vertical specialization on hierarchical multi-agent systems. In: Proceedings of the 23rd AAAI conference on artificial intelligence, pp 138–143

Russell S, Norvig P (2002) Artificial intelligence: a modern approach. 2nd edn. Prentice Hall

Shafaei S, Aghaee NG (2008) Biological network simulation using holonic multiagent systems. In: Tenth international conference on computer modelling and simulation, pp 617–622

Simão JM, Stadzisz PC (2009) Inference based on notifications: a holonic metamodel applied to control issues. IEEE Trans Syst Man Cybern Part A 39(1):238–250

Simão JM, Tacla CA, Stadzisz PC (2009) Holonic control metamodel. IEEE Trans Syst Man Cybern Part A 39(5):1126–1139

Sycara KP (1998) Multiagent systems. AI Mag 19(2):79–92

Tannenbaum AS (2006) Structured computer organization. 5th edn. (c) 2006 Pearson Education

Thompson D, Hughes DR (1998) Holonic modelling. Manuf Eng 77(3):116–119

Tichy P, Slechta P, Staron RJ, Maturana F, Hall KH (2005) Multiagent technology for fault tolerance and flexible control. IEEE Trans Syst Man Cybern C Appl Rev 36(5):700–705

Ulieru M, Este RA (2004) The holonic enterprise and theory emergence: on emergent features of self-organization in distributed virtual agents. Cybern Hum Knowing 11(1):79–98

Van Dyke Parunak H, Odell J (2002) Representing social structures in UML. In: International workshop on agent-oriented software engineering, vol 2222. Montreal PQ, Canada, pp 1–16

Walker SS, Brennan RW, Norrie DH (2005) Holonic job shop. Scheduling using a multiagent system. IEEE Intell Syst 2:50–57

Wooldridge M, Jennings NR (1995) Intelligent agents: theory and practice. Knowl Eng Rev 10(2):115–152

Xiaokun Z, Norrie DH (1999) Dynamic reconfiguration of holonic lower level control. In: Proceedings of the second international conference on intelligent processing and manufacturing of materials, vol 2. pp 887–893