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Emergent Phenomena in AmI Spaces

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Abstract. *This work aims at a) identifying the forthcoming changes in our everyday life due to the ever-increasing level of complexity that inculcates our interactions with the devices surrounding us, b) introducing a bio-inspired world model (framework) that deals with different perspectives of the interrelations developed in symbiotic ecologies where people and artefacts coexist, and c) proposing a high level architectural scheme of an AmI space reflecting the basic ingredients of the future indoors/outdoors applications based on Swarm Intelligence and Complexity Science.*

Keywords: Complex Systems, emergent behaviour, Ambient Intelligence, Swarm Intelligence, Ubiquitous Computing

1 Introduction

The vision of Ambient Intelligence (AmI) implies a seamless environment of computing, advanced networking technology and specific interface ([9], [11]). In one of its possible implementations, technology becomes embedded in everyday objects such as furniture, clothes, vehicles, roads and smart materials, and people are provided with the tools and the processes that are necessary in order to achieve relaxing interactions with this environment. The AmI environment can be considered to host several Ubiquitous Computing (UbiComp) applications, which make use of the infrastructure provided by the environment and the services provided by the AmI objects therein.

An important characteristic of AmI environments is the merging of physical and digital space (i.e. tangible objects and physical environments are acquiring a digital representation). As the computer disappears in the environments surrounding our activities, the objects therein become augmented with Information and Communication Technology (ICT) components (i.e. sensors, actuators, processor, memory, wireless communication modules) and can receive, store, process and transmit information [11]. The AmI objects differ from traditional objects in that they can communicate with other AmI objects and can interact with the environment. Of special interest is the information that AmI objects process, which can be descriptions of the context of use, data to be used for a task, guidelines on how to perform a task, messages to be sent or that have been received from other objects. The result of information processing is a set of services, that is, a set of abilities that appear in the digital space and relate to information.

On the road to becoming an AmI space, our living space as of today is already populated by many devices, which are able to process (and sometimes store) and communicate digital information. These are divided in three major categories [8]:

- The PC Internet world where PC and PC peripherals communicate.
- The broadcast world that serves set-top boxes and traditional consumer electronics, e.g. TVs, VCRs, stereo systems, CD/DVD players etc.
- The mobile world, consisting of multimedia mobile phones, PDAs, laptop computers and similar devices, that provides unparalleled connectivity and freedom of movement into and out of the home environment.

A new fourth category, as a consequence of the gradual realization of the AmI vision, is the white-goods devices, like refrigerators, microwaves ovens, air-conditioners, etc, which recently is including everyday objects enhanced with sensing, processing and communication abilities.

This work builds upon the envisaged structure of AmI environment as one populated by thousands of communicating tangible objects and virtual entities [13]. Following an agent-oriented programming approach [21], we can classify them into active, in the sense that they have an explicit goal to achieve (i.e. a TV has a goal to display a selected broadcast, an air-conditioner has a goal to maintain a certain air temperature, etc) and passive. The latter are those being used as part of tasks (i.e. numerous everyday objects surround us like tables, chairs, walls, photo frames etc), according to the plan of active objects (e.g. a wall may be used to hang a poster out or to project a video). At a minimum, AmI environment will contain network infrastructure will be available that will make anytime, anyplace (within boundaries of acceptability) interaction among and with these objects feasible.

2 Research Issues and Requirements

The heterogeneity of AmI objects make necessary the development of middleware systems on top of which UbiComp applications can function transparently with respect to the infrastructure [13]. In order to preserve the autonomy of AmI objects and to cater for the dynamic nature of UbiComp applications, ad-hoc networking has to be supported; thus, no specific network infrastructure can be taken for granted. The underlying physical networks used are heterogeneous ranging from infrared communication over radio links to wired connections. Since every node serves both as a client and as a server (devices can either provide or request services at the same time), the required communication can be considered as peer-to-peer [12].

As a consequence of the dynamic nature of UbiComp applications and of the mobility of AmI objects, the middleware has to use services and capabilities with changing availability

[14]. In addition, even a service that is both functional and reachable can become unavailable (the volatility problem). As objects of all sizes are candidate components of ubiquitous computing applications, the enabling middleware has to be adaptable to the physical properties (e.g. size, power) in the case of tangible objects and computational abilities (e.g. memory) of a broad range of devices [10].

Since UbiComp applications operate within an extremely dynamic and heterogeneous environment, the context definition, representation, management and use become important factors that affect their composition and operation. UbiComp applications have to dynamically adapt to changes in their environment as a result of users' or other actors' activities. To ease the development of such applications it is necessary to decouple application composition from context acquisition and representation, and at the same time provide universal models and mechanisms to manage context [7].

Current digital paradigms for interacting with the digital world are often inadequate and are leading towards a dead-end of frustration-in-use and impoverished digital living. This situation will deteriorate once computers become dispersed into everyday environments; interaction problems will be significantly multiplied and shift towards a different, under-explored territory of paradigms that originate from having to interact with hundreds interacting nodes, many of which will be physically imperceptible. Additionally, as computational power diffuses in our living/working environment and the everyday devices that are capable of sensing, processing and communicating continuously grow in numbers, new requirements are posed by i) the people who use UbiComp applications, ii) the heterogeneity of the involved devices, and iii) the large number of the involved devices.

As a consequence, key research challenges have to focus in services availability including both services aimed at end users as well as machine to machine services, and to deal with dynamic composability and adaptability, context awareness, autonomy and semantic interoperability. Essentially, new research issues arise concerning i) the system complexity emerging by the thousands local interactions between people and artefacts, ii) the need for flexible and dynamic system architecture capable to evolve and adapt to new situations and configurations, iii) the context dependence of the exchanged information, and iv) the human involvement and especially new, more natural, human-machine interaction schemes.

The abovementioned features impel to the development of a framework that will help ordinary people deal with the complexity of using UbiComp applications that will exist within AmI environment, and especially assist them in dealing with the interactions occurring therein. The framework must be capable to host and reflect transparently the available services as well as the potential use of the participating objects. Although the available services may somehow be exhibited, the potential use of the objects emerges mainly from the interactions of the humans with the active and passive devices and these interactions are not only time-dependent but also space- or context-dependent. Specifically, the framework should employ a scheme based on five premises:

- An easy-to-understand-and-use end-user programming model, which will build upon known world models, interaction metaphors and usage concepts.
- The exploitation of locally stored knowledge into the surrounding devices as well as the AmI environment.
- A classification mechanism based on attributes of social behaviour of the components of UbiComp applications.
- Procedures for distributed decision making, which will facilitate the emergence of UbiComp applications as compositions of collaborating services, with or without the explicit intervention of the humans.
- A composition mechanism of previous successful/failed actions aiming at feeding back the UbiComp applications.

The next sections set the scene of a near future everyday living/working environment and describe an engineering approach inspired by biological structures capable to deal with phenomena arising in such an environment. Subsequently, a related high level architectural scheme is introduced. A depiction of the involved technologies and associated research directions follows and the paper concludes summarising the most prominent elements of this work.

3 Proposed Conceptual Framework

A living/working AmI space comprising of many heterogeneous objects with different capabilities and provided services could be considered that is populated by a *heterogeneous swarm*. There are many potential benefits of such an approach including greater flexibility and adaptability of the system to the environment, robustness to failures, etc. The swarm will comprise different typologies of societies, and so it will be heterogeneous also from the provided services point of view. Such differences will contribute to the overall capabilities of the system. As a general principle, the services should be as simple as possible, according to the concept of summing the capabilities of extremely simple members by the swarm system increasing the number of agents, sharing the resources and maximizing the effectiveness of the communication. Ideally, the composition should emerge based on previous interactions and on the context (time and place) they took place.

From a macroscopic perspective, a natural system (or ecology) consisting of thousand living organisms exhibits superiority, in terms of stability, coherency, flexibility and adaptability, because these organisms are integrated and optimized with respect to their computation and control strategies, morphology, materials, and their environment (see details in http://www.neuro-it.net). The participants (or organisms) are deployed in such an ecosystem where coherent choices are manifest across the whole space of options, rather than just at the computational/control level. These organisms live, obey rules and reap the benefits of a society of kin. Societies may vary in size and complexity but they share a common property: they provide and maintain a shared culture. Intelligent creatures create and refine social rules in order to perpetuate the society. These rules constitute a culture which is communicated and shared by the society, and has important effects on the individual members. In this context individual intelligence needs to be analyzed within its social and therefore cultural environment.

An ecology is defined by the environment it resides in, the members it consists of, and the interactions between the members and the environment. In detail, an *ecology* is i) concerned with the interrelationship of organisms and their environments, ii) the totality or pattern of relations between organisms and their environment. Thus, the members of an ecology are the *organisms*, meaning i) complex structures of interdependent and subordinate elements whose relations and properties are largely determined by their function in the whole, ii) individuals constituted to carry on several activities by means of organs separate in function but mutually dependent. Advancing in more detailed decomposition, each organism is composed of *organs* that are i) differentiated structures performing some specific function in an organism, ii) bodily parts performing a function or cooperating in an activity, iii) parts of an organism that have been adapted to perform a specific function. Finally, the fundamental ingredients of the organ are the *cells*, which are elementary units capable alone or interacting with other cells of performing specific functions, and forming the smallest structural unit of a matter capable of functioning independently.

For engineering such problems and in an attempt to create a metaphor of the biological structures and principles into the information systems, the traditional Artificial Intelligence (AI) focused on addressing intelligence as an individual phenomenon. This approach considers (intelligent) agents with cognitive states which maintain a (partial) model of the world they inhabit in and a (partial) model of the others. These agents are usually autonomous, social and try to accomplish tasks they are designed for [23]; in any case, the deliberation and the activation of these kinds of agents are based on their maintained models of the world and of the others. Despite of many interesting results, the abstractions made by this approach, led to isolated and disintegrated solutions regarding the development of large-scale intelligent artificial systems. A radical different approach is based on the belief that intelligent behaviour is inextricably tied to its cultural context and cannot be understood in isolation. Indeed, many natural systems can be described in terms of many individually “simple” components, interacting in “simple” ways and influencing their neighbours, and yet, are able to exhibit “complex” overall system level behaviour; those systems that exhibit this “emergent” globally complex behaviour from simple components are referred to as “complex systems” [6]. In contrast to traditional Artificial Intelligence, Swarm Intelligence (SI) is defined as the emergent collective intelligence of groups of simple agents, or in more detail, SI is the property of a system whereby the collective behaviours of (unsophisticated) agents interacting locally with their environment cause coherent functional global patterns to emerge ([3], [15]). As an engineering approach, SI offers an alternative way of designing intelligent systems, in which autonomy, emergence, and distributed functioning replace control, pre-programming, and centralization.

Thus, when focusing on situated social systems in dynamic and non-deterministic environments, it is very hard (if not aimless) to embody into each organism complete models of the environment and of the others. Alternatively, none explicitly represented world models could be considered ([4], [5]); all the necessary information is out there changing dynamically and as so the world is the model itself. All we need is the means to capture, qualify and exploit the information that surround us. In order to deal with the collective behaviour of large ecologies in situated domains, a recent approach is the analysis and synthesis of small pieces of primitive behaviours that result from individual interactions.

Inspired by the biological social systems (ecologies), the analysis of artificial swarm systems could range in different levels depending on the desired granularity. For example, in a macro-scale domain where many autonomous and heterogeneous agents interact, every single agent could be considered as a single behaviour building block which models a set of primitive behaviours [16]. Every single agent has specific capabilities and therefore the members of the society could play the role of sensors, actuators and computation building blocks leading to both physical and functional construction. In this two-level granularity, the agents are the organisms that constitute the ecology. In a three-level granularity, the specialised agents could form structures resembling to organs (e.g. for sensing, acting etc) and thus the swarm becomes an abstract loosely coupled organism and several swarms constitute an ecology. From another perspective, the society could be formed (or modelled) as a neural network (sensors/actuators building blocks representing the input/output neurons and computation building blocks representing hidden neurons) that can learn and evolve [17]. Now, the whole network is the ecology, the neurons are the organisms and the synapses between neurons represent the local interactions of the organisms. A third perspective is to consider the large amount of (different) artefacts as sensor networks owning limited power, computational capacities and memory. Sensor networks are densely deployed, have not global identification (ID), and their topology changes very frequently. Based on their (limited) processing abilities, instead of sending raw data, they may locally carry out simple computations and transmit only the required and partially processed data [1]. Hence, the combination of sensor networks with artefacts with computing and effecting capabilities may trigger the continuous formation of new societies that provide services not existing initially in the individuals and exhibiting them in a consistent and fault-tolerant way.

Independently of the analysis level, the computational capabilities (and the intelligence) of the ecology are distributed over the central “nervous” system, the peripheral system, the materials of the ecology’s body and the physical phenomena created by the interaction of the ecology with its environment. Putting such entities into a UbiComp environment could lead to **extelligent ecologies**, where knowledge and tools are diffused in the environment [22], underlying thus the **corporal literacy** of the ecology, meaning the awareness of the extelligence and the working knowledge of all senses. This will pave the way for the generation of theory and technology of **synthetic phenomenology** (of the resulting ecology) meaning the understanding of the own self and its relation with the surrounding world (Fig. 1).

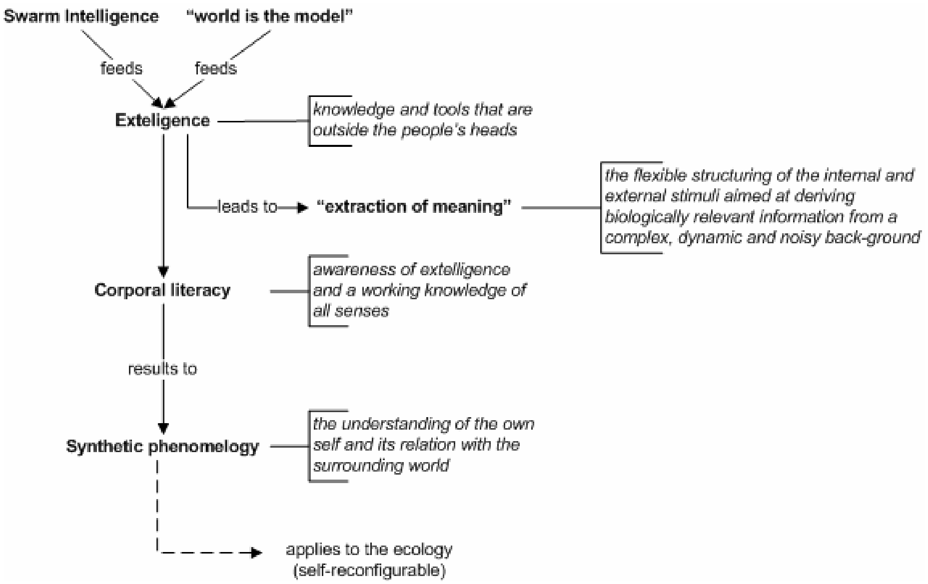

Fig. 1. Concepts relations on how dynamic changes of the environment and local interactions can lead to self-awareness.

Drawn from the above, the proposed high level architectural scheme that consistently reflects bio-inspired self-aware emergent symbiotic AmI space ecologies consists of the following ingredients (Fig. 2):

Basic building blocks: Everything can be regarded as a potential building block of a larger system, including sensors, hardware resources, software modules, artefacts. Every building block has an internal part, which is proprietary and possibly closed, and an external part, which is public or manifested as an influence to the environment, thus making the building block open to use or perceivable. Thus, building blocks are structures with physical and functional specification, capable to perceive the environment they reside in and to act upon it.

Ecologies: Groups of building blocks, their interrelationships and the associated environment form the ecologies. This means that ecology is more the configuration of the elements, rather than the elements per se. Although the members of the ecology have only local perceptions and local interactions, the ecology acts as a whole, which is not necessarily more than the sum of its parts but undoubtedly different from them (Gestalt Theory). The behaviour of ecology is not determined by that of its individual elements, but where the part-processes are themselves determined by the intrinsic nature of the ecology.

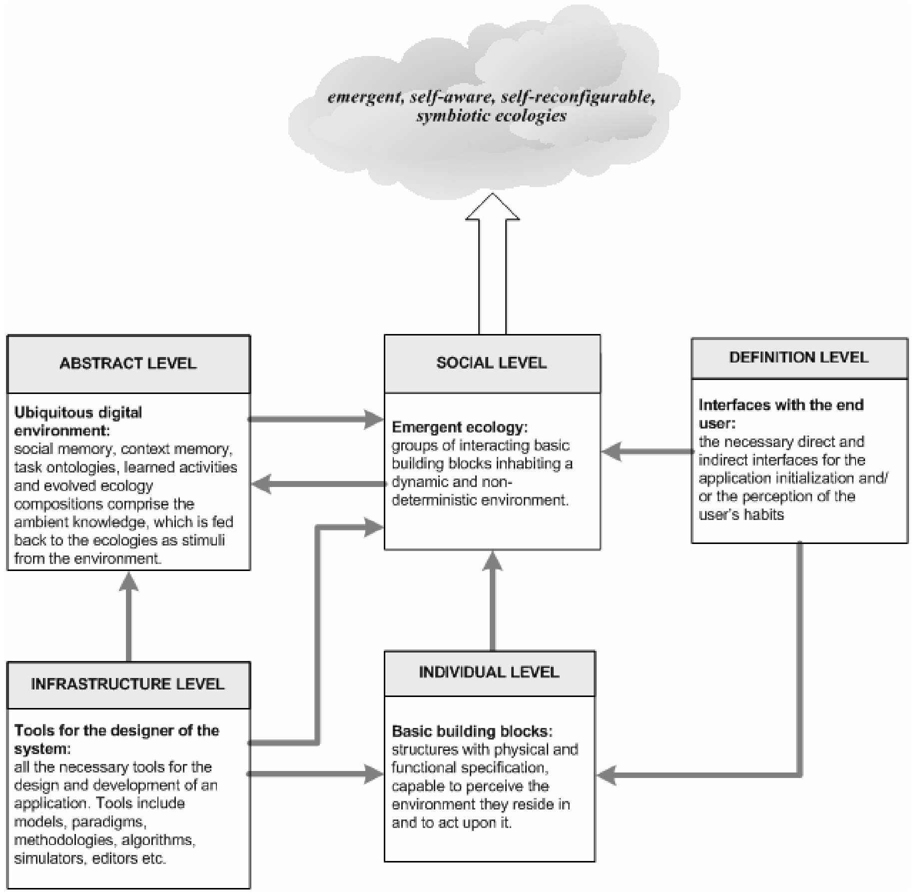

Fig. 2. High level architecture of the system. Individual and Social levels correspond to the basic building blocks and ecologies, respectively. Abstract level encloses the social memory of the ecologies; such knowledge must be transferred to the ecologies implicitly e.g. as stimuli of the environment, since individuals and consequently the emergent ecologies do not contain any knowledge representation scheme neither reasoning mechanism. Infrastructure level provides system designers with the appropriate tools to develop a system. Definition level is the user interface with the final user.

Ambient knowledge: It includes decentralised coordination models and selective interaction models which provide the abstractions and mechanisms for (i) environmental and context state reuse and reasoning, (ii) social and cultural memory representation, (iii) knowledge and experience interchange. Emergent behaviour, in this context, is considered to be as a result of some form of consensus on a shared view of the environment enabled by interactions among heterogeneous, potentially arbitrary entities. Thus, ambient knowledge paves the way to emergent consensus as a substitute for social and cultural memory. Emergent consensus on a common view of a shared environment by interacting entities is a basis for establishing collective behaviour or complex adaptive system behaviour. Ambient knowledge is fed back to the ecologies as stimuli of the environment.

People: The involved users can be divided into several different categories such as building block developers, hardware designers, artefact manufacturers, applications developers and end-users. As each of these categories plays a different role in the system and has a variant perception for the world model, they are divided into two classes.

The first class includes the people that create the infrastructure of the system that includes models, theories, architectures, algorithms, behaviours, knowledge, protocols, mechanisms, interfaces etc. Thus, this category includes all the people that take part in the procedure of "creating" the building blocks and pose the driving force for the emergence of the ecologies. People of this category fall into architecture designers, building block designers and developers, knowledge engineers and hardware designers. Essentially, they perceive the world as a set of building blocks, architecture models, behaviours, shapes, proposed services, paradigms and guidelines, which will use in order to develop a variety of building blocks and ecologies.

The second class includes the end-users that use/cohabit with the ecologies. The end-users can play more than one role, as they can only use the provided building blocks and ecologies or they can co-create applications based on their own needs and desires. Thus the end-users can partly adapt and/or configure applications in order to compose personalised applications. The people of this category perceive the world as a set of symbiotic ecologies, which can be initialised and can learn and self-adapt according to their needs.

4 Instruments

Along these lines and aiming at building complete UbiComp systems, which make optimum use of distributed intelligence embedded in the periphery (sensors, actuators, body morphology and possibly materials), the involved theories, technologies and scientific communities are undoubtedly interdisciplinary. It is mentioned that the aimed outcome is the development of self-aware and self-reconfigurable symbiotic ecologies where artificial beings and humans coexist. The applications consist of tangible entities and ubiquitous services applied in indoors and outdoors areas. Particularly, the applications include autonomous software populating autonomous devices where the social interactions arise among the different elements and adaptation to unforeseen (at design time) situations encountered in dynamic environments is needed. The abovementioned aim requires the establishment of a commonly accepted paradigm of the life-cycle (specifying, designing, developing and integrating) of the artefacts participating in this type of ecologies. In more detail, the following steps are involved in the establishment of a well defined framework for the development of self-aware and self-reconfigurable symbiotic ecologies.

1. *Formulation and development of bio-inspired models and theories focusing on emergence, modelling cognitive and awareness processes, physical growth, and ontogenesis.*

These will help to design, construct and experiment with the interacting basic building blocks that will constitute the aimed ecologies. Clearly, a fostering research and synergistic work is needed between a broad range of scientific fields such as cognitive/experimental neuroscience, cognitive/developmental psychology, biological cybernetics, neuroinformatics and IT communities. A bio-inspired conception must be adopted based on the natural laws of evolution, survival and reproduction. Models relating energy, perception, computation, local interactions and interface plasticity must be studied in order to help in a counterbalance of low-energy consumption and sufficient capacity of extraction of meaning. This will pave the way for the generation of theory and technology of synthetic phenomenology (of the resulting ecology) meaning the understanding of the own self and its relation with the surrounding world. The accomplishment of these tasks involves i) the development or the refinement of dynamic bio-inspired specification models that describe how local behaviour becomes global and how to control it/reverse it or even how global strategies transform into local ones, ii) the specification of the morphology, "primal instincts" and limited capabilities of the artefacts inspired by the natural organisms that enable them to interact and cohabit with the others, iii) the specification of a minimal set of building blocks having certain physical properties and exhibiting certain behaviours, which will allow coherent society development and also the control of the communication between the participating individuals so that they can develop a desired behaviour and capabilities through their interaction with the environment.

2. *Development of a methodology on how to construct autonomous entities with "flexible structuring of the internal and external stimuli" and an integration framework that leads to the realization of self-reconfigurable ecologies.*

The techniques must be focused on intelligent periphery, morphology and possibly materials, inspired by the wide range of intelligent adaptations in non-human (neural) systems, gathering and exploiting knowledge about the world and the tasks, "environment models" used to codify world/task knowledge. By allying theoretical aspects such as the abovementioned to more practical bio-inspired technology driven aspects, the aim is to obtain a large understanding of social systems that learn from observing and from interacting with other more advanced systems. Key issues that have deep functional and economic significance for the design, construction, and maintenance of emergent ecologies include i) learning and evolution in an embodied artificial system; ii) autonomous self-construction and growth of artefacts ("epigenetic robotics"); iii) adaptation to the environment (possibly over several generations), and iv) robustness in performance. The tight multi-disciplinarity naturally addresses issues such as the practical limits of intelligent systems, the essential properties of networks and sensors, the emergence of the complexity phenomena and how to control and profit from complex systems.

3. *Design and implementation of ambient knowledge/experience repositories available as substitutes of social memory.*

This could also contribute to the higher level cognitive processes including self-awareness, learning, and adaptation. As the symbiotic societies are dynamically reconfigured aiming at the accomplishment of new tasks (targeting to satisfy a higher goal), their formation heavily depends not only on space and time but also on the context of previous local interactions, previously configured teams, successfully achieved goals or failures. This means that in order to initially create, manage, communicate with, and reason about, such kinds of emergent ecologies, we need somehow to model and embed to these entities social memory, enhanced context memory, and shared experiences. These models should provide the appropriate abstractions and mechanisms for i) context reuse and reasoning, ii) social memory representation, and iii) knowledge and experiences inheritance. One step to this end is the design and implementation of evolving multi-dimensional ontologies that will include both non-functional descriptions, and rules and constraints of application, as well as aspects of dynamic behaviour and interactions. A core ontology could be open and universally available and accessible; however, during the ecology life-time the core ontology may be evolved into higher goal, application and context specific one [7]. Hence, ontologies describing specific application domains could be proprietary. Emerging behaviour, in this context, might be considered as a result of interactions among heterogeneous, seemingly incompatible or non pre-defined entities. Moreover, all higher-level constructions could be inherently able to use all the knowledge they will be able to access.

4. *Development of the necessary tools that constitute a development environment.*

New innovative concepts must be introduced and must be supported by specialized tools integrated in a development environment. The emergent ecologies must be based on the notion of the “autopoietic machine” built from basic building blocks (or cells in terms of genetics) [18]. Therefore, tools that provide representation schemes from physical world to digital space, learning and evolution mechanisms, communication protocols, and interaction patterns must be implemented and integrated in a development environment. The development environment will support the creation, management, communication with, and reasoning about, the emergent ecologies. Furthermore, it will apply novel methodologies for engineering the autonomous entities at different granularity levels. New programming paradigms are necessary (e.g., subject-oriented programming with subjects that are born, have a life cycle, can diminish, and have internal goals and intensions).

5 Engineering Emergent Phenomena

An especially complex task is to model and build autonomous interactive entities that could form extelligent ecologies exhibiting corporal literacy and leading to a synthetic phenomenology approach. The task is additionally complicated by considering that the resulting ecologies will operate into a ubiquitous environment and will be driven by autonomy, local perceptions and interactions, emergence, and distributed functioning. An important aspect on this focus is that although the entities will not have explicitly represented models of the world or of the others the emergent ecologies will unfold coherent collective behaviour based only on the entities' own agenda of actions and their intrinsic inclination to preserve their own goals.

Realizing the potential benefits of the UbiComp applications populated by autonomous simplistic entities will require improvements in currently available technology platforms and a translational research paradigm from basic-research findings. Hence the driving force behind the whole idea focuses on the adaptation of concepts from complex biological systems and novel fabrication technology platforms to build truly innovative swarm robotic systems for emerging real-life applications. Technological challenges posed by this approach and the investigative methodology to overcome them are described below.

5.1 Basic building blocks development

As described above, several levels of abstraction are possible for the formulation of the basic building block. Immediately, the engineer strives with the questions on i) which should be the basic building block, ii) what structural and functional properties it should encompass, iii) how it could interact with the others, and iv) how it could be realised. From a technology development point of view, an essential plan is needed which initially centres about the basic building block and considers as such every self-sustained digital (h/w or s/w) artefact with certain functionality that can operate without the contribution of others. That type of artefacts could be robots with pre-defined specialised capabilities, or could be sensors, motors, computational sources etc. In both cases emergent ecologies are possible to be formed exhibiting capabilities not found in the individuals.

Undoubtedly, this "macro" or high level perspective does not deal with issues as the structural parts, the realisation approach or the interaction patterns of the basic building blocks. Rather, such issues could be studied by disciplines such as artificial neural networks [2], evolutionary robotics [20] and machine learning [19] concentrated on building intelligent control systems. On the other hand, the problem-solving concepts from social systems in nature could be analysed and adapted for technical applications by using simulations. Simulation environments could give the possibility to study artificial ecologies of bio-inspired entities to close the capability gap between natural information processing systems and human-made ones. Additionally, they could help to reveal fundamental interrelations between rules for entities of intelligent ecologies and the resulting global behaviour. Instead, as the focal point remains at the range of the behaviours that a basic building block should manifest, then the engineering methodology and the development starting point should be driven by the primitive behaviours approach followed in robotics applications. According to this approach, the overall behaviour of the system becomes the emergent effect of the interaction with the environment and the coordination of the primitive behaviours.

5.2 Engineering emergent behaviour

In dynamic environments, an individual must be reactive, that is, it must be responsive to events that occur in its environment, where these events affect either the individual's goals or the assumptions, which underpin the procedures that the individual is executing in order to achieve its goals. However, what turns out to be hard is building a system that achieves an effective balance between goal-directed and reactive behaviour. Furthermore, as the construction of the individuals must be based on the development of primitive behaviours, the issues of how to select potentially the correct behaviours in different circumstances and how to resolve conflicts between them are raised. The primitive behaviours approach considers that all the (individual) behaviours run in parallel and depending on the stimuli of the environment some of them manifest themselves by enabling a suppression mechanism and taking control of the actuators. However, this technique requires a pre-defined and exhaustively tested set of implicit rules (usually encoded into finite state automata) of firing priorities. Thus, this technique does not scale well even in moderate number of primitive behaviours and it lacks learning even in very often tasks.

In order to apply the well-established primitive behaviours approach in swarm societies that can learn and evolve component-oriented principles and practices could be employed. Synthetic behaviour control mechanisms could be developed based on bio-inspired approaches like spiking neural networks. These behaviour control mechanisms responsible for the arbitration and/or the composition of the primitive behaviours could also be subject of learning and evolution. The individuals may exhibit varying behaviour – capable of perceiving/exploring their environment, selectively focusing attention, initiating and completing several tasks. The learning and evolution could be studied and investigated at both the individual and social levels. In this case, the focal point must be the components of behaviour control mechanisms. The outcome could contribute to a novel dynamic and adaptive architecture of swarm systems that exploits the global effects through local rules/behaviour.

5.3 Engineering collective behaviour

Developing a robust swarm system, capable of exhibiting emergent intelligent collective behaviour is a non-trivial task. The nature of the social/collective behaviour sought and the environment that allows efficient development of ecologies requires research. In building a swarm system communication plays a pivotal role and this explains the profuse number of publications in this area.

A flexible and light-weight approach is the indirect (stigmergic) communication. The essence of stigmergy is that the individual modifies a local property of the environment, which subject to environmental physics, should persist long enough to affect the individual's behaviour later in time. It is the temporal aspect of this phenomenon, which is crucial for emergent collective behaviour (collaborative exploration, building and maintenance of complex insect nest architectures etc) in societies of ants, agents and robotics. Thus, the individuals could be provided with the proper periphery (actuators/sensors) enabling them to emit/perceive electromagnetic signals emulating thus the biological "quorum sense" signals. Such a quorum sense communication may be based on an application-specific vocabulary that will be encoded in the signal. The specifics of the temporal modulation aspect of this "quorum sense signal" will come from theoretical biology and existing simulation studies. Additionally, the frequency of the signal will be determined after studying the combined influence of the physical medium properties, the range and interference constraints, power requirements and the size of available hardware components.

6 Summary

As everyday objects are being enhanced with sensing, processing and communication abilities, the near future of our everyday living/working is indicated by a high degree of complexity. The emergent complexity concerns the machine-machine and human-machine interactions as well as the provided services aimed at end users and at other machines. Into this rapidly changing AmI environments new requirements and research issues arise, and the need for a conceptual and analysis framework is apparent. This work attempts to introduce a bio-inspired word model that draws features from natural systems and applies them into symbiotic ecologies inhabited by both humans and artefacts. Furthermore, it introduces a high-level architecture of AmI spaces that encloses the fundamental elements of bio-inspired self-aware emergent symbiotic ecologies.

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