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Design for Emergence – A new Paradigm for Cognitive Systems

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1. Executive Summary

The research area at the intersection of natural and technical cognitive systems is emerging and challenging. Despite significant success in some related areas, a break-through in the understanding, modelling and integration of cognitive capabilities into a cognitive artificial system is still missing or mostly restricted to systems designed to perform simple tasks of limited scope in "sunshine" environments.

This document presents a research roadmap in the area of intelligent cognitive systems. It defines challenges and deficits in this field of research and proposes a new paradigm whereby we can move beyond the current status. According to the proposed paradigm, research in cognitive systems should be carried out in the context of understanding the processes that lead to autonomous growth and development of the cognitive systems and goes beyond task-orientation. In this context, semantics will arise from the interaction of an agent with its environment and other agents. Along that direction, four research themes and several major research lines within each theme have been indentified:

- Processes and representations for emergence (system internal view)
- Emergent cooperation (system external view)
- Embodiment for guiding design (system basis and frameworks view)
- Principled benchmarks (system evaluation view)

The key issues underneath the identified research themes are (a) the need to understand the environment that shaped human evolution in order to understand design requirements, (b) and how humans combine mechanisms that evolved at different times to meet different requirements and (c) the need to understand more varieties of information-processing mechanism than have so far been developed.

2. Introduction

The third Working Group (WG3) "Intelligent Cognitive Systems" of the European Coordination Action InterLink (http://interlink.ics.forth.gr) is concerned with the identification of challenges and the proposal of future research directions in the field of intelligent cognitive systems. The contents of this document are the product of the four InterLink workshops organized by WG3 and the discussions carried out among recognized experts in the field who contributed directly or indirectly to its contents. The workshops took place:

- in Eze, France (May 2007),
- at the Artificial Intelligence Laboratory,University of Zurich, Switzerland (November 2007)
- at the Southern University of California (USC), USA (September 2008)
- in Cannes, France (November 2008).

The proposed research roadmap has been compiled based on the discussions and position statements of recognized experts who participated in these workshops.

2.1 Motivations

The successful attempts in building artificial intelligent cognitive systems are still mostly restricted to systems designed for "sunshine" environments having limited scope and performing simple tasks. The transferability of the developed skills and abilities to varying contexts and tasks without costly redesign of specific, ad hoc solutions is still impossible. Therefore, key research activities in the future should be devoted (a) to the definition of rich cognitive challenges which are measurable and scalable in open-ended scenarios under changing conditions and (b) to the development of measures, metrics and benchmarks that highlight and focus on transferability as well as performance.

Currently, an encouraging spectrum of many isolated elements in the area of cognitive systems is realizable (vision, speech, learning, decision making, planning, motor control) with a focus on performance in well defined, narrow domains (chess, calculus, narrow dialogs, handling of few objects). The technological progress in the fields of computer architectures, mechatronics, and sensor systems allow for the first time the building of truly intelligent systems that perceive, reason, understand, and learn. Such systems will be useful for extracting meaning from huge data flows; thus addressing one of the key emerging challenges of human participation in "Information Society", namely the information overflow problem. Truly intelligent cognitive systems should be able to operate in an autonomous way, naturally interact with their environment and the humans therein, and be (self-) adaptive to changing situations and contexts, including the user's preferences and needs.

First and foremost, it became clear that a break-through in the understanding, modelling and integration of cognitive capabilities into a cognitive artificial system is still missing and that this ultimate goal can only be achieved through efforts that span a wide range of disciplines from the field of human and artificial cognitive systems. It became also clear that Europe has the potential to play a leading role in the analysis and modelling of cognitive systems due to the leading position of European research in the fields of computer vision, neuroscience, cognitive science and robotics. In Europe we are in particular able to gather the required critical mass of leading scientists in interdisciplinary consortia[1], thus making it possible to address challenges of scientific as well as commercial relevance. However, the existing expertise in information theory, neuroscience and social sciences can be more strongly bundled to provide better theoretical foundations towards understanding the processes and underlying mechanisms on which cognition builds. It is hoped that through extensive international collaboration, a fruitful cross-fertilisation will emerge, giving technical oriented scientists new inspiration from biology and providing cognitive scientists with new ways to prove and evaluate their biological models.

In Europe, research efforts in the area of cognitive systems are currently supported by a big number of projects (see http://cordis.europa.eu/fp7/ict/cognition) are funded under Cognition Unit (E5) to advance the development and construction of artificial cognitive systems that "*should learn and develop through individual or social interaction with their environment. The work should provide an enabling technology that applies across domains such as natural language understanding, image recognition, automated reasoning and decision support, robotics and automation, sensing and process control, and complex real-world systems. The work should furthermore borrow insights from the bio-sciences, and yield innovative insights about perception, understanding, interaction, learning and knowledge representation*." The funded projects cover a wide range of disciplines in cognitive science research: cognitive architectures, object, scene, and event recognition and interpretation, behaviour modelling, planning, reasoning, and learning, robot-robot and human-robot interaction, humanoid robots, manipulation, and grasping. This European initiative provides the largest funding support for cognitive systems research and worldwide unique example to promote the field.

1.2 Drives and Technological Disciplines

We identified two groups of disciplines related to developing cognitive systems: *driving disciplines*, which provide the ideas and motivation for research, and *technological disciplines*, which provides the necessary enabling technologies.

Figure **1** shows one view of the scientific disciplines related to developing cognitive systems. A break-through in the understanding, modelling and integration of cognitive capabilities into a cognitive artificial system requires coordinated and integrated research efforts that span a wide range of disciplines such as learning theory, control theory, human-machine-interaction, mechatronics, perception (both computational and psychological), biomechanics and neuroscience. These fields have usually been explored independently, leading to significant results within each discipline. The cross-fertilization among these disciplines for the building of technical cognitive systems requires enormous collaborative resources and can be achieved only through long-term, multidisciplinary research programs.

The research on humans in both neuroscience and psychology acts as a drive for the study of cognitive systems since it provides with inspiration on how artificial cognitive systems can be structured. In fact, humans themselves provide an excellent example that learning and adaptation are necessary to cope with the complexity of the world. This type of inspiration is extremely valuable because, as the current and past experience demonstrates, it is not probable that pure engineering approaches will be able in producing systems with substantial cognitive capabilities. On the other hand, we believe that exact emulation of the human neurological structure is not necessary or even feasible because of the differences in embodiment of technical and biological cognitive systems.

[1] see http://cordis.europa.eu/fp7/ict/cognition for an overview of the European cognitive systems projects

Figure **1** does not cover all the technological disciplines used to develop cognitive robotic systems. Instead, the intention is to illustrate the major *enabling technologies* that have to be addressed in future research agendas towards building cognitive systems.

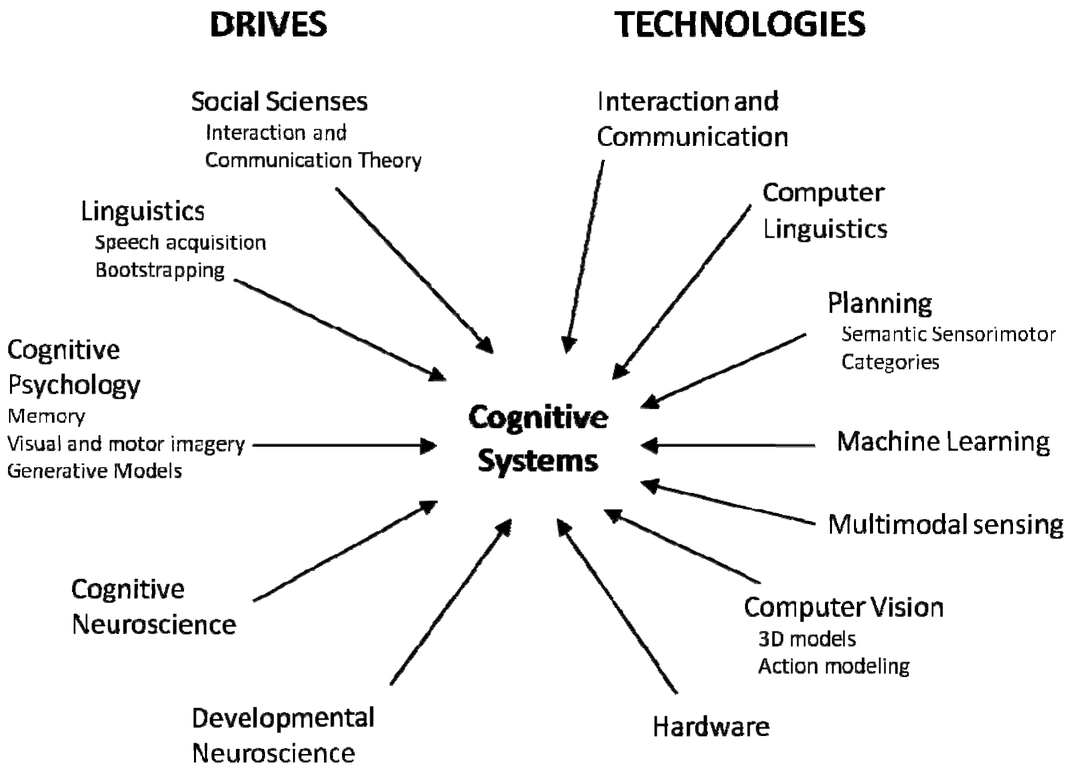

Figure 1 Drives versus technological disciplines

1.3 Evaluation and Organization of the document

The first important step of the activities of the Working Group was the preparation of the "State-of-the-Art" Report, which results from the first two workshops held in may 2007 in Eze, France and in November 2007 at the Artificial Intelligence Laboratory at the University of Zurich in Switzerland. In the state of the art report (STAR), we identified major research areas and challenges in cognitive systems research.

In September 2008, a third workshop was held at the University of Southern California, LA, USA. The third Workshop was held at the University of Southern California, USA. The goal of the workshop was two-fold. First to discuss the state-of-the-art report with cognitive systems experts from the US and determine what needs to be revised and how to go about doing that, and second to discuss research topics of the roadmap for research in cognitive systems and to explore possibilities for international cooperation.

In Section 2 of this document, the identified challenges in cognitive systems research are briefly. The resulting output was discussed at the forth workshop in Cannes in November 2008. In this workshop, the Working Group identified the need for a new approach to cognitive system development that needs to break away from the blueprint idea. Instead of focusing on the system development, such approach should concentrate on understanding processes that lead to autonomous growth and development of the system. Furthermore, the underlying concepts of such approach should go beyond task-orientation and provide a framework, in which semantics will arise from the interaction of an agent with its environment and other agents. The resulting research themes and the research lines in each theme are described in Section 3 of this document.

3. New Issues and Challenges

In the state of the art report (STAR), we identified major research areas and challenges in cognitive systems research. The identified challenges can be summarized as follows

- Methodologies supporting the *development of systems that explore their own sensorimotor primitives, body morphology, the environment and the effective interaction with it*. Technologies should also facilitate the systems capability to predict the body dynamics and the physics of the world and, thus, lead to the ability of reasoning about it.
- Methodologies supporting *learning of new skills, adapting already acquired skills and switching between different learning modalities*. For this purpose, scientific and technological foundations must be addressed to provide frameworks and representations, which allow for combining multiple forms of learning and context-depend switching between such forms of learning. These methodologies and frameworks should allow for competence learning as well as autonomous and interactive skill and strategy transfer to varying contexts and tasks.
- *Architectures and models* for the representation and organization of huge bodies of knowledge for sophisticated sensory-motor control, choosing and combining actions, and for coping with common everyday situations.
- *Cognitive architectures* that allow the integration of perception, action, reasoning, learning, and communication components thus providing the underlying infrastructure for complete systems.
- Technologies for *soft sensors, massive connections, soft flexible tissues* (tendon-like, skin-like, bone-like) which allow the realization of adaptive, flexible, and robust artificial cognitive systems and provide safe interaction with humans.
- *Common/shared complex platforms* with standard/common/open-software, which on the one hand allow researchers from different field to evaluate their theories and on the other hand provide a framework for benchmarking of different algorithms, which is a fundamental issue but extremely difficult yet.

Based on this, three thematic themes were identified:

- *Cognitive Representations* which allow for learning and extending representation in ways that transform intractable problems into tractable ones and support generalization and knowledge transfer between different cognitive systems. These representations should take into account space and motion, objects (things that move) and actions, properties and affordances, goals, plans, beliefs and desires, communication, models of other minds.

- *Human-Robot Interaction (HRI):* The field of Human–Robot Interaction has received growing attention in the recent years and a real community is developing worldwide, as demonstrated by the increasing number of networking initiatives and dedicated events. A key aspect in this field is multimodal interface technologies, which allow to "observe" humans and their environments by recruiting signals from the multiple audio-visual sensors. A fundamental issue in the context of human-robot interaction is the natural multimodal interaction, based on visual person localization and tracking and for gesture and posture recognition, speech recognition, and dialogue processing. Additional aspects include the role of HRI for assistive domains (home, public, etc), personalization, proactivity, emotion, social behaviour, self-awareness, and autisme diagnoses.

- *Platforms and Systems:* Open, affordable and/or accessible platforms are a prerequisite to study cognitive systems research questions. Such platforms should have a reference model or architecture with varying degree/level of access. Together with reference model, reference data sets and common software repositories, benchmarking will become a scientific approach of evaluation. To study various aspects in cognitive systems a set of platforms (mobile robot, robot arms, hands, ambient environments, etc) is necessary. Challenges in this context are the development of new materials for the platforms, new actuators, new sensors (in particular tactile sensors) and high density lightweight power sources.

For the advancement of the state of the art in the field, the Working Group identified the need for a new approach to cognitive system development that needs to break away from the blueprint idea. Instead of focusing on the system development, such approach should concentrate on *understanding processes that lead to autonomous growth and development of the system*. Furthermore, the underlying concepts of such approach should go *beyond task-orientation* and provide a framework, in which *semantics will arise from the interaction* of an agent with its environment and other agents.

4. New paradigm for cognitive systems - Design for Emergence

As stated above, WG3 identified the need for a new approach to cognitive system development that needs to break away from the blueprint idea. Instead of focusing on system development, one has to concentrate on **understanding processes that lead to autonomous growth and development of the systems and goes beyond task-orientation**. **Semantics will arise from the interaction of an agent with its environment and other agents**. Therefore four key research themes have been indentified to structure the processes for understanding natural cognition and for engineering of cognitive systems. The research themes are:

- Processes and representations for emergence (system internal view):
- Emergent cooperation (system external view)
- Embodiment for guiding design (system basis and frameworks view)
- Principled benchmarks (system evaluation view)

The key points for the identified research themes are:

- The need to understand the environment that shaped human evolution in order to understand design requirements since most of the rich collection of features of the environment determining requirements for cognition have never been described, such as spatio-temporal structures, relationships, processes, including multi-strand relationships and multi-strand processes. There are many aspects of human cognition that evolved originally to meet requirements for 3-D vision and action — including intricate manipulations of 3-D structures — using exosomatic ontologies. The mechanisms and forms of representation are now used for many other purposes, and can be used by people who have been blind from birth or who were born without limbs.

- The need to understand how humans combine mechanisms that evolved at different times to meet different requirements. The most general capabilities of humans, which are those provided by evolution, and which support all others, develop during the first few years of infancy and childhood. We need to understand those in order to understand and replicate the more 'sophisticated' and specialised adults that develop out of them. Attempting to model the adult competences directly will often produce highly specialised, non-extendable, and probably very fragile systems because they lack the child's general ability to accommodate, adjust, and creatively re-combine existing competences.

- The need to understand more varieties of information-processing mechanisms than have been developed so far.

The four research themes will be addressed in the following subsections in more detail.

4.1 Processes and representations for emergence (System internal view)

An important aspect for future cognitive systems is the definition of morphogenetic processes (processes that causes an organism to develop its shape) for information processing, which takes into account the processes of cooperation, stabilization, consolidation, focusing, categorization, and mode selection. Self-scaffolding will be a powerful mechanism for learning to extend representations in ways that transform intractable problems into tractable problems. Autonomous, interactive and incremental learning and co-developmental approaches will be a key element in the development of processes for emergence. For this purpose, one has to study how to organize sensorimotor experiences into appropriate data structures that allow sensorimotor learning at different levels of abstraction.

Key aspects will be the alignment and coordination of representations of space and motion, objects (things that move) and actions, properties and affordances, goals, plans, beliefs and desires, values, communication, embodiment, and even models of other minds. The emergent representations should allow generalization, transfer, sharing, and extensibility of knowledge.

Another line of research that should provide significant progress over the state of the art will be the active learning of object categories, where one has to combine visuomotor capabilities of artificial systems (gaze fixation, foveation, manipulation, grasping) with hierarchical feature representations to automatically learn object categories. Moreover, guided by research in

neurophysiology as well as developmental psychology, one has to define mechanisms for the autonomous grounding of object affordances. These mechanisms will become embedded into a cognitive architecture in which syntactic bootstrapping (Gleitman 1990) will allow for the grounding of increasingly complex affordances as well as their interaction with higher levels of reasoning (e.g., planning).
One particularly promising way for knowledge extension is the employment of developmental approaches to generate semantic sensorimotor categories constituting the experience of the system. This begins with head-eye-hand coordination, progressing through manipulation, and extending to inter-agent communication. This process is, generally speaking, data-driven, starting from action and perception, to acquire an ever enlarging set of sensorimotor categories. These categories can be seen as the elemental token of exchange with higher level cognition (Clark, 2001). Fundamentally, these developmental processes rely on learning and adaptation; the motivation to exercise the motor system plays a key role in the unfolding of the developmental process.

In the following three representative research lines within this research theme are proposed and described. The proposed research lines are:

- Semantics representations
- Perception-action coupling
- Cognitive architectures

4.1.1 Semantic representations

Traditional psychological and artificial intelligence models of natural cognition studied cognition mainly at the level of higher-level symbol manipulation. This approach suffers from the grounding problem (Harnad 1990) by disregarding the connection between the representations and their real-world referents. In the past, the acknowledgment of these problems led to a fundamentally different approach to building intelligent systems in the field of artificial intelligence. Rather than focussing on higher-level intelligent behaviour by means of computations performed on abstractly represented knowledge, the new so-called "situated" approach focuses on low-level behaviours in situated agents acting within an environment (see e.g. Brooks 1986, Beer 1995; Clancey 1997; Pfeifer & Scheier 1999; Pfeifer & Bongard 2006). The new situated artificial intelligence approach to cognition, often called "embodied cognition" (Wilson 2002), thus moved the modelling of intelligent systems from the study of isolated, representation-rich, symbol manipulation systems, to the study of the dynamics of agents and their interactions with the environments. By contrast to the traditional Cartesian view on artificial cognition in AI, for the new models developed in the field embodied cognition, the cognitive psychology of human high-level behaviour remained the main source of inspiration. Currently, the fields are slowly moving towards each other. On the one hand artificial intelligence is exploiting the advantages of extending their agents to incorporate more complex cognitive structures such as memory systems. On the other hand, the findings from the new embodied cognition approach inspire models of the field of cognitive psychology by increasingly considering the essential role of the environment for cognition (e.g. Pecher & Zwaan 2005). Adhering to these global developments, the emergence of semantic representations for a situated cognitive system that operates directly within a natural environment, must be investigated by addressing the problem of grounding of perception by action (see e.g. Fitzpatrick et al. 2003) and the grounding of language in the interaction of such agents (see e.g. Steels 2003).

In humans, sensorimotor knowledge is gained from childhood on, beginning when children explore the space around them with seemingly random movements. This type of learning is the focus of developmental approaches, which have gained a lot of attention in robotics in recent years (Pfeifer & Scheier 1999; Kuniyoshi et al., 2003; Lungarella et al., 2003; Metta et al., 1999; Pfeifer & Bongard 2006). Once a sufficient amount of data has been accumulated, more informed learning approaches can be applied such as imitation learning (Schaal, 1999) supplemented by motor-practicing, which can take place in the form of reinforcement learning maximizing a suitable reward (Peters and Schaal, 2008).

In parallel to the development of motor capabilities, the processing of sensory data also gradually improves, like for example the visual system, which through time enhances its discrimination capabilities as well as the perceived spatial resolution (Lungarella, 2003). Linking action and perception seems crucial to the developmental process that leads to this specific competence (Fitzpatrick and Metta, 2003). It has been shown that the integration of visuomotor processes aids the acquisition of object knowledge (Kraft et al., 2008; Ude et al.; 2008). The next step that needs to be taken is to combine these results with research in computer vision that showed that a general categorization system capable of recognizing a large number of object categories requires the hierarchical structuring of information (Fidler et al., 2008; Ullman & Epshtein, 2006).

4.1.2 Perception-action coupling

Research into cognitive systems should combine the study of perceptual representations that facilitate motor control, motor representations that support perception, learning based on actively exploring the environment, as well as interacting with people, where all this provides the constraints of perception and action. This will then allow, e.g., to learn the actions that can be carried out on and with objects by making use of the interplay of different sensory modalities, such as vision, haptics and acoustics. Action-centred cognition presupposes that artificial cognitive systems will be equipped with eyes, sophisticated haptic sensors for its end-effectors and microphone-ears. This allows for efficient interaction with the world making use of the full potential of multi-sensorial representations.

In traditional information theory, the environment only plays the part of a passive, undirected disturbance (for example also in *closed loop* control theory) negatively affecting the input-to-output transfer characteristics of a system. Here we propose, instead that *the environment should be treated as an active component.* It is active through “my own actions” (the actions of *ego*) and those of “the others” (the actions of *alter*), which feed back to ego. Thus, traditional information theory is not sufficient to describe correctly the interaction of an agent with its world. Instead, this problem needs to be addressed in a closed loop paradigm where ego acts in its environment and observes the consequences of its actions (in interrelation also with alter). This notion has entered modern robotics theories by the qualitative term “rootedness”, which refers to the necessity to embed an artificial acting agent in an environment. Thus, instead of using the conventional I/O paradigm, this new approach introduces so called *encased closed loop* situations, defined by the mutual interactions of an organism (ego) with its environment. An encased closed loop describes a conventional sensor-motor feedback control loop but with an active environment monitored from the perspective of ego. This represents a central shift of paradigm and follows a constructivist’s viewpoint where *the environment becomes an integral part of the system’s description.* This notion goes clearly beyond the conventional concept of a perception-action loop. It embeds the agent into its environment and into its social group by the same formalism. On the side of theory this will lead to intrinsically *consistent and* *technologically applicable measures of "autonomy", "contingency", and "complexity"* of agent-world- as well as agent-agent interactions, resulting in the first steps towards an information theory of encased closed loops.

4.1.3 Cognitive architectures

In addition to studying processes and representations for emergence, investigations are necessary of how to build integrative cognitive system architectures, which should provide a framework for modelling, validation, and benchmarking of cognitive systems. Although the literature demonstrates successful implementations of early cognitive systems, no attempt has been reported so far to build a complete cognitive architecture as an underlying infrastructure for cognitive systems able to learn, adapt and perform task in changing environments. Nor has anyone seriously tried to relate the cognitive architecture to developmental and neuroscientific data as well as, simultaneously, to validate such an approach on a complex robotic platform.

New architectures should allow the use of emergent representations and substitute the modelling of cognitive systems based on the study of isolated, representation-rich, symbol manipulation systems with the study of the dynamics of agents and their environments. Together with semantic representations this will allow bridging representational gaps between high-level symbolic and low-level sensorimotor representations. Thus, this will also provide theory and engineering principles for sensorimotor grounding.

An important aspect that must be addressed, concerns the question of how to memorize and internally represent data and make it accessible to the different sensorimotor processes in an efficient way. The realization of different memory architectures, inspired by neurophysiological and psychological findings on the mechanisms and knowledge structures, must be evaluated in real environments and tasks. The knowledge representation and the memory architecture must provide a framework for the linking of low-level sensorimotor processes to high-level symbolic planning and to the decision making level. Open questions are still how to implement short term, long-term, and episodic memory systems in artificial cognitive systems.

One of the major problems in rigorously testing architectures lies in their developmental nature. As an example, the assumptions they make about the emergence of cognition in the course of phylogenetic (evolution) and ontogenetic (learning) development, are extremely difficult to test empirically. Therefore, it is of crucial importance to create the conditions for testing such theoretical models and to transfer the obtained findings into artificial cognitive systems.

4.2 Emergent cooperation (System external view)

Cooperation between agents will have to be based on the principles of alignment, entrainment, imitation, sharing, anticipation, and proactive interaction. Guiding principles of cooperative decision making and role assignment in teams of cognitive agents "cognitive ensembles" must be investigated to bootstrap natural communication and language generation. New theories of interaction should be developed to enable human-robot, human-human, human-robot-human, robot-robot and other forms of interaction.

In the following **three representative research lines** within this research theme are proposed and described. The proposed research lines are:

- Human-Machine Interaction

- Language and Communication
- Self-X Systems

4.2.1 Human-Machine Interaction

The field of Human–Machine Interaction has received growing attention in the recent years and a real community is developing worldwide, as demonstrated by the increasing number of networking initiatives and dedicated events. In particular the field of Human-Robot Interaction (HRI) is a quickly growing research area with numerous applications in assistive technology and service robotics. Some of the key research questions in this field are:

- Multimodal interface technologies, which allow "observing" humans, other agents and their environments by recruiting signals from multiple audio-visual sensors. A fundamental issue in human-robot interaction, is natural multimodal interaction based on vision for person localization and tracking and for gesture and posture recognition, speech recognition, and dialogue processing. Systematic evaluation of multimodal human-robot interaction technologies is essential to drive rapid progress in this crucial field.
- New methods to carry out and analyze human-robot interaction in different scenarios (robots as companions and helpers at home, robots as assistive technology, robots in personal care and health care, etc). Key research issues are the adaptation of the cognitive system behaviour to the individual needs and preferences of the user. A personalized robot companion needs to know its users, and to be able to adapt in long-term interaction. Personalization, role distribution, and intention recognition are additional research topics in the field.
- Regardless of the application scenario, autonomous and interactive agents have to operate in human-centered environments and play a beneficial role in the daily lives of people. Crucial aspects of agent-design are in fact the modalities, mechanisms, techniques, and tools for human–robot interaction, for communication with human beings, with the environment, possibly with other robots, and for interaction with human environments, modelled on persons' needs and habits, and not slanted towards the robot functions.

4.2.2 Language and Communication

Computational work on learning natural language, such as Roy, 1999, Steels 2004, Steels and Bailie 2003, has shown that techniques for natural language learning can be applied to realistic examples and physically embodied robots. However, such work has generally used a fixed logical language for meaning representations, in order to demonstrate that the mapping of sensory data to grammar can be efficiently learned. What is much harder to show is whether logical forms with the characteristics necessary to support learning of actual human grammars can be induced de novo from situated sensory-motor experience, and what innate structures, if any, are required to make such induction possible. Part of the problem is that the relation between syntax and semantics in most theories of grammar is sufficiently indirect as to leave us uncertain as to what exactly those semantic characteristics are.

Thus, advancement of the state-of-the-art in automatic, semantically grounded grammar acquisition to constrain the space of possible theories is an important aspect, where research efforts should be devoted.

4.2.3 Self-X Systems

The term "Self-X systems" denotes systems that have the capabilities of self-assembly, self-organization, self-reconfiguration, self-repair, self-replication, or self-reproduction. The field of Self-X systems is extremely promising for advances in different areas such as manufacturing, bioengineering, evolutionary software and new computer architectures. The big challenge in such systems is to capture principles of collective operation, such as altruistic cooperation, dynamic division of labor, emerging communication, role assignment, and shared representations, as for example in ant colonies. This implies an updated and global knowledge of the needs of the colony, which is not yet realistic for a robot with only imprecise and local sensory information.

One of the strengths of self-X systems is their potential ability to respond to uncertain environments and execute a variety of tasks. Hence, research activities to analyze the response of robotic self-X systems to partial system failure and uncertain or changing environments are of crucial importance. Technologies that allow such systems to operate optimally in the presence of uncertainty, adapt to changes in the external environment, and respond rapidly to applied disturbances and disruptions to the internal system states are important because systems equipped with these advances can learn, adapt, evolve, and achieve resiliency to large-scale environment or state variations. Further research topics can be formulated as follows:

- Morphology variations in self-assembling systems to accomplish changing goals.
- System adaptation through repeated self-organization.
- Scalability of hardware and control algorithms in self-reconfigurable systems.
- Learning and minimization of module self-repair.
- Self-replication in unstructured environments.
- Evolutionary behaviors that result from self-reproduction.
- Coordination between different types of self-X systems.

4.3. Embodiment for guiding design (System basis and frameworks view)

The development and emergence of cognition relies on artificial embodiments having complex and rich perceptual and motor capabilities. This makes biologically inspired artificial (robot) systems the most suitable experimental platform for studying cognition. Body morphology of artificial cognitive systems should be inspired by biological systems. The body morphology must support processes and representations for emergence. Such systems will be able to learn its own body schema and cope with morphological changes arising through physical interaction with the environment.

Self-organization and self-reconfiguration, redundancy, robustness and flexibility are of great importance for the development of concepts and scientifically grounded theories toward the implementation of complete artificial cognitive systems. This necessitates new design principles and further development of sensor technologies (of artificial skin in particular) soft, compliant and energy efficient actuation methods, as well as self-reconfigurable software and hardware architectures (i.e. dynamically reconfigurable on-chip multi-core systems).

In the following **two representative research lines** within this research theme are proposed and described. The proposed research lines are:

- Humanoid Robots
- Robot Ensembles

4.3.1. Humanoid Robots

The development of cognitive robots relies on artificial embodiments having complex and rich perceptual and motor capabilities. This leads to humanoid robots as the most suitable experimental platform. While simpler robotic systems might be more suitable for testing some theories in simplified environments, only humanoid robots can provide rich sensorial inputs and complex actions necessary to develop higher cognitive processes.

Personal humanoid robots is a key growth industry of the 21st century. The big challenge is the advancement of robotics technologies to the point where interactions between humans and robots run smoothly and robots are able to fulfil roles in the human living space. These robots will act together with humans in a human-centred everyday environment and serve as human assistants and life-long companions.

The design of such robots which are capable of developing perceptual, behavioural and cognitive categories in a measurable way, of communicating and sharing these with humans and other artificial agents is a challenging task. The target system is supposed to interact and function together with humans. It is meant to be able to cooperate and to enter a dialogue with them. Therefore it needs to understand both what it perceives and what it does. Such understanding can only be attained if we consider the human in the loop.

Although current systems are technologically advanced, they are not able to learn in an open-ended way and their behaviours are limited. Moreover, they are not based on some firm theory that allows the systematic development of capabilities. One can hardly see these systems as any generic steps towards systems with cognitive capabilities.

However, internationally there is a great awareness of the potential impact that cognitive systems could have in the shape of robots. In Japan, researchers have for a long time been working on systems that could be of use to an aging population, especially as human companions. Still, up to now, these systems cannot be characterized as truly cognitive. It has been increasingly recognized by both the industry and the research community that robots for personal use must become more humanlike to have a chance of being accepted by non-specialists. This is reflected in national humanoid robot projects in Japan, Korea and Europe as well as by various extensive research programs in the United States. Major Japanese companies such as Honda and Toyota have already developed humanoid robots. Although these platforms have not yet been turned into commercial products, it is clear that the decision that robots coming into our future personal and professional environments will have to posses many human-like features, has already been made. One of the reasons for this interest is the belief among many, that intelligent and social robots will both provide a growth industry as well as enhance the creation of new, *human-centered* technologies. Another reason is the motivation that this is a key application of today's technology from an economical and social point of view. The research on building such systems will both engage in the production of these new technologies but also contribute to the education and training of individuals who will be able to exploit the new technologies.

4.3.2 Robot Ensembles

The vision of multiple, inexpensive robots operating in concert to solve complex and dynamically changing tasks has not yet been materialized. From a scientific / technological perspective, the two major challenges can be identified a) in developing efficient and general models of collective operation and b) in conceiving hardware for disposable and collective operation.

Although many models of collective operation (swam intelligence) have been proposed, those are mostly applicable to specific robotic hardware and tasks. The big challenge is to capture principles of collective operation, such as altruistic cooperation, dynamic division of labor, and emerging communication, applicable to a wide set of robotic platforms and tasks. Even when a general model exists in the biological literature, that model is not easily applicable to a real robot. For example, the response threshold model often used to explain division of labor in insect societies implies an updated and global knowledge of the needs of the colony, which is not realistic for a robot with only imprecise and local sensory information. It is therefore necessary to bring together scientists from biology, control theory, and robotics to develop principles and algorithms that hold in the reality of specific robots and animals. At the same time, these must be general enough to be easily applicable to novel platforms. The generality of the proposed solution should be demonstrated in more than one validation scenarios. It would also be interesting to look at multiple scales, ranging from cells to societies and from evolution to life-long adaptation.

Most artificial systems (e.g. robots) for collective operation are realized using the same design principles of robots that operate in isolation. This is also true for modular robots which, despite their different structure, still rely on classic mechatronic principles, such as rigid connections and joints that are difficult to fabricate. Consequently, the large scale deployment of robots for collective operation is often not competitive with an alternative solution that relies on a single, more complex robot. At the same time, these robots do not always take full advantage of the fact that they should work collectively. It is therefore necessary to carry out a thorough study of the principles of hardware design, physical connection, and communication in living systems in order to design a novel generation of robots.

4.4. Principled benchmarks (System evaluation view)

Evaluation and benchmarking scenarios in the field should go beyond task-orientation to consider satisfying instead of optimization and emergence of competence in different environments and transferability of such competence between different systems. Human developmental stages (6 months, 12 months, ...) should serve as a guidance for the development of artificial cognitive systems and the principled benchmarks to evaluate the growth of the system. To develop a research roadmap with principled benchmarks, one could observe feats of humans (e.g. young children, playing, exploring, communicating, solving problems) and other animals (e.g. nest-building birds, tool makers and users, berry-pickers and hunters). These provide many existence proofs, not of specific mechanisms, but of a wide variety of possible behaviours for intelligent embodied individuals i.e. requirements to be met by the designed systems.

In the following **two representative research lines** within this research theme are proposed and described. The proposed research lines are:

- Grasping and manipulation
- Integrative studies of cognitive systems

4.4.1. Grasping and Manipulation

Compared to humans or primates, the ability of today's robotic grippers and hands is surprisingly limited and their dexterity cannot compare to the human hand capabilities. Contemporary robotic hands can grasp only a few objects in constricted poses under limited grasping postures and positions. Although there is an abundance of artificial hand designs ranging from one to eighteen degrees of freedom (DOF), replicating the effectiveness and flexibility of human hands in object manipulation tasks undoubtedly requires a fundamental re-thinking of how to exploit this mechanical dexterity. Recent psychophysical and neurophysiological findings suggest that the central nervous system adopts simplifying strategies to reduce the complexity of hand control. Furthermore, neuroscientists and cognitive scientists build models of how perceptual and motor cortex work.

The challenge is the design of cognitive systems capable of performing grasping and manipulation tasks in open-ended environments, dealing with novelty, uncertainty and unforeseen situations. Therefore, studying the problem of object manipulation and grasping will provide a theoretical and measurable basis for system design that is valid in both human and artificial systems.

In addition, exploiting the theoretical findings by investigating the grasp mapping to different artificial hands will contribute to learning how kinematical design and the number of DOF influence dexterity and how to optimize the graspable sub-set of all possible grasps while minimising the number of DOF. This shall ultimately lead to efficient hand designs that are suitable for low cost production to aid as many handicapped persons as possible. It shall also influence future manufacturing of robotic hands useful to industrial as well as service-oriented enterprises.

4.4.2. Integrative Studies of Cognitive Systems

In the last years, the different disciplines related to the development of intelligent cognitive systems have usually been explored independently, leading to significant results within each discipline. However, the big challenge is how different pieces of results fit together to achieve complete processing models and an integrative system architecture (Brooks 1991, Newell 1973; see also Gray 2007). Many scientists focus all their efforts at one level of design – physical, neural, cognitive, social, etc. or at most two levels, e.g. neural and behavioural. Such research can be too narrow minded and doomed to get things badly wrong because small successes can mask big gaps and errors in theories (Hubert Dreyfus: climbing trees is not necessarily evidence of progress towards a moon landing).

Progress can only be made through intensive dialogue among researchers from the fields of natural and artificial cognitive systems. Apart from theories of cognition, special emphasis must be put on experimental studies, approaches for comparison, analysis, and synthesis of various cognition paradigms. Experimental studies of intelligent cognitive systems need test-beds that allow the evaluation of behaviours and results at system level rather than focusing on the performance of component algorithms. Such test-beds together with common repositories must be provided for use by the research community. Examples of such repositories are the UCI Machine Learning Repository (Blake and Merz 1998) and the iCUB repository of the RobotCub project (http://eris.liralab.it/iCub/).

5. Cross-thematic group synergies

The InterLink Coordination Action consists of three Working Groups: Software Intensive Systems and New Computing Paradigms (WG1), Ambient Computing and Communication Environments (WG2) and Intelligent and Cognitive Systems (WG3). The research topics of the WG3 are tightly coupled with those of the other Working groups. In the following we describe the cross-thematic synergies of the proposed research directions in WG3 with those identified in the other two Working groups WG1 and WG3.

5.1 Software Intensive Systems and New Computing Paradigms (WG1)

In both areas “Software Intensive Systems and New Computing Paradigms” and “Intelligent Cognitive Systems” there are several common research topics related to self-reconfiguration, resource allocation in embedded systems and/or in robot ensembles.

Intelligent cognitive systems should be able to learn to operate in the real world and to interact and communicate with humans. They have to model and reflectively reason about their perceptions and actions in order to learn, act, predict and react appropriately. To perform these tasks in a real world, especially in real-time, demands substantial high computing power that support situation-dependent context switching between different applications and the processing of the large amount and variety of sensory data in parallel and allocate resources appropriately.

5.2 Ambient Computing and Communication Environments (WG2)

In both areas “Ambient Computing and Communication Environments” and “Intelligent Cognitive Systems” there are several common research topics related to learning methods, adaptation strategies, interaction and communication technologies, social human-robot interaction distributed situation assessment.

Ambient intelligence (AmI) is an exciting new information technology paradigm in which people are empowered through a digital environment that is aware of their presence and context and is sensitive, adaptive, and responsive to their needs. The underlying vision assumes very large numbers of "invisible" small computing devices embedded into our environment. They will interact with and being used by multiple users in a wide range of dynamically changing situations. In addition, this heterogeneous collection of devices will be supported by an “infrastructure” of intelligent sensors (and actuators) embedded in our homes, offices, hospitals, public spaces, leisure environments providing the raw data (and active responses) needed for a wide range of smart services. In these environments, a multitude of interconnected, invisible embedded systems, seamlessly integrated into the background, surround the user. The system recognizes the people that live in it and programs itself to meet their needs by learning from their behaviour.

6. Suggested instruments for international cooperation

The realization of artificial cognitive systems requires enormous collaborative resources and can be achieved only through long-term, multidisciplinary research programs. We see three major possibilities for international cooperation:

- Joint research projects, organized with a cross-national emphasis to achieve both strong research collaboration and results, but also to ensure cross-cultural fertilization and internationalization of the faculty, students and staff.
- Coordinated actions, organizing workshops, seminars and summer schools on international level.
- Broader educational and research opportunities for faculty and researchers to exchange knowledge and jointly train students in an environment of international immersion, where researchers get to know each other and then collaborate. Among the many opportunities for joint educational programs there may be such as short-term academics, distant and distributed collaboration and educational exchange programs.

7. Summary of recommendations

The understanding and design of intelligent cognitive systems requires numerous efforts in different disciplines. In this section we summarize the topics and research themes that requires immediate investigation and/or further investigation in the field of cognitive systems and propose

1. Representations: Alignment and coordination of representations of space and motion, objects (things that move) and actions, properties and affordances, goals, plans, beliefs and desires, values, communication, embodiment, and even models of other minds. Such representations should allow should allow knowledge generalization, adaptation, transfer, sharing, and extensibility.

2. Cooperation: Cooperation between agents will have to be based on the principles of alignment, entrainment, imitation, sharing, anticipation, and proactive interaction. Principles of cooperative decision making and role assignment in “cognitive ensembles” must be investigated to bootstrap natural communication and language generation. New theories of interaction should be developed to enable human-robot, human-human, human-robot-human, robot-robot and other forms of interaction.

3. Embodiment: The body morphology must support processes and representations for emergence. Self-organization and self-reconfiguration, redundancy, robustness and flexibility are of great importance for the development of concepts and scientifically grounded theories toward the implementation of complete artificial cognitive systems. This necessitates new design principles and further development of sensor technologies (of artificial skin in particular) soft, compliant and energy efficient actuation methods, as

well as self-reconfigurable software and hardware architectures (i.e. dynamically reconfigurable on-chip multi-core systems) and high density lightweight power sources.

4. Benchmarking: Evaluation and benchmarking scenarios in the field should go beyond task-orientation. To develop a research roadmap with principled benchmarks, one could observe feats of humans (e.g. young children, playing, exploring, communicating, solving problems) and other animals (e.g. nest-building birds, tool makers and users, berry-pickers and hunters).

Methodology and research tools to be addressed:

- Build a family of reference platforms (both simulated and physical instantiations) with sufficiently large number of degrees of freedom as well as standard and rich interfaces.
- Build common software repositories including data sets.
- Define *n* independent tasks (see example tasks below).
- Design a population of different fixed cognitive agent configurations.
- Compete on the suite of tasks with cognitive/representational design held constant
- Evaluate
    - Performance across the task corpus.
    - Monotonicity of cumulative learning, i.e. suite of *n* tasks should have a (semi)positive influence on task *n+1* regardless of task order
    - Evaluate the invariants constructed in various cognitive configurations.
    - Measure transfer between tasks as a function of training/learning sequence.

Example tasks

- Learn collision-free motion strategies to rewarding places in environments of varying scale.
- Learn mobility modes that traverse irregular indoor terrain
- Learn to push, grasp, and pick up a wide variety of object geometries
- Learn to make a stack of objects (what multi-body relations predict stacks)
- Learn what objects can be inserted into other objects.
- Clean up a room, sort objects into bins
- Learn to transport large numbers of small objects (using container as a tool).
- Learn gestural/verbal means of conveying goals, means, intentions, and constraints between a human and a robot.
- Collaborate with a human peer when human and robot have asymmetrical roles and functions
    - Reach high places
    - Pick up heavy/large objects
    - Clean under the bed

8. Conclusions

This deliverable has presented proposals for future research directions in the area of intelligent and cognitive systems. Special emphasis has been placed on identifying the processes that lead to autonomous growth and development of the systems and goes beyond task-orientation. Following the paradigm – Design for Emergence - semantics will arise from the interaction of an agent with its environment and other agents. Four research themes with several research lines within each theme have been identified and discussed.

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Annex B: List of Participants in the Workshops

Participants and organizers of the four workshops of WG3 “Intelligent Cognitive Systems”

1. Workshop in Eze, France, May 2007

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2. Workshop in Zurich, Switzerland, November 2007

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3. Workshop in Santa Monica, LA, USA, September 2008

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4. Workshop in Cannes, France, November 2008

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