



**ERCIM**

European Research Consortium  
for Informatics and Mathematics

# InterLink

International Cooperation  
Activities in **Future**  
and **Emerging ICTs**



February 2010



# Introducing InterLink

To attract and foster trans-disciplinary research excellence, research programmes need to be defined around new grand challenges and/or key technological issues that have major economic importance or are derived from major societal drivers. Such programmes should explore visionary research themes, demand breakthroughs in basic research and engineering in key technologies and investigate radically new uses for technology.

The Coordination Action InterLink, 'International Cooperation Activities in Future And Emerging ICTs' (Contract No. 034051), funded by the Future and Emerging Technologies (FET) Programme of the European Commission, had a duration of 32 months (1 Oct 2006 to 31 May 2009). The InterLink consortium consists of five partners: European Research Consortium for Informatics and Mathematics (ERCIM, coordinator), Foundation for Research and Technology – Hellas (FORTH, scientific coordinator), Ludwig-Maximilians-Universität München, Fraunhofer-Gesellschaft Integrated Publication and Information Systems Institute, and Universitaet Karlsruhe.

The main goals of InterLink were to:

- bring together internationally renowned scientists and highlight the latest advances in their areas
- facilitate the exchange of experiences and discussion of the latest progress and findings in challenging research problems relevant to the selected thematic areas
- collectively identify new research topics
- link European research communities to the best research carried out in other developed countries in the respective research fields



*Prof. Constantine Stephanidis  
ICS-FORTH, Director  
InterLink Scientific Coordinator*

- enable European researchers to access knowledge, skills and technology available outside the EU
- provide a critical assessment of the advantages and disadvantages of different kinds of international collaboration
- promote European solutions and knowledge worldwide and influence the way in which science and technology evolve internationally
- build new international strategic alliances, wherever this may be of benefit to European efforts
- influence the design of new research programmes to be funded by the EC, and also by other funding agencies worldwide
- broadly disseminate the findings of InterLink at a European and international level.

Three thematic areas have been carefully selected based on the need to address the evolution of the Information Society in the next ten to fifteen years and the challenges this imposes on computing, software engineering, cognition and intelligence. For each thematic area, a Working Group (WG) was established, and these worked in a coordinated fashion. They had a scientifically and geographically balanced participation, involving experts, mainly from the academic and research sectors, representing various research practices and innovation strategies, from Europe, North America, Australia, Asia and the Far East.

There are three InterLink thematic areas:

**1. Software intensive systems and new computing paradigms** (WG leader: Dr. Martin Wirsing, University of Munich, Germany; deputy leader: Dr. Matthias Hölzl, University of Munich, Germany). The continuing decrease in the cost of micro-processors and storage is leading to the development of more distributed and decentralized systems. Society's dependence on software-intensive systems is increasing to the point where a growing range of products and services from all sectors of economic activity, but also daily life, depend on software-intensive systems. Applications will be assembled as dynamic federations of autonomous and evolving components. In this context new computing paradigms and techniques are required for building software-intensive systems.

**2. Ambient computing and communication environments** (WG leader: Dr. rer.nat.Dr.phil. Norbert Streitz, Smart Future Initiative, Germany; deputy leader: Dr.-Ing. Reiner Wichert, Fraunhofer IGD, Germany). The evolution of the information society is characterized by the development of personalized individual and collective services that exploit infrastructures situated in smart environments and that are based on a range of ubiquitous and pervasive communication networks, providing ambient computing at multiple levels. The underlying vision of pervasive and ambient computing assumes very large numbers of minute computing devices embedded into the environment, interacting with multiple users in a wide range of dynamically changing situations, and supported by an 'infrastructure' of intelligent sensors (and actuators) that are also embedded in the built environment. The realization of this

vision requires advances in various areas of ICT, necessitating highly multidisciplinary research.

**3. Intelligent and cognitive systems** (WG leader: Prof. Ruediger Dillmann, University of Karlsruhe, Germany; deputy leader: Dr. Tamim Asfour, University of Karlsruhe, Germany). Cognitive systems should be able to interpret data arising from real-world events and processes, acquire situated knowledge of their environment, act, make or suggest decisions, and communicate with people on human terms. The design of cognitive artificial systems requires coordinated and integrated research efforts that span a wide range of disciplines and need collaborative resources that can be achieved only through long-term, multidisciplinary research activities.

A number of workshops were organized by the InterLink consortium:

- InterLink opening workshops, Eze, France, 10-12 May 2007
- second series of thematic area workshops:
  - Ambient computing and communication environments, 5-7 November 2007, Eltville-Hattenheim, Germany
  - Intelligent and cognitive systems, 15-16 November 2007, University of Zurich, Switzerland
  - Software-intensive systems and new computing paradigms, 3-4 December 2007, Munich, Germany.
- third Series of thematic area workshops:
  - Ambient computing and communication environments, 18-20 June 2008, Tokyo, Japan
  - Software-intensive systems and new computing paradigms, 28-29 July 2008, Urbana-Champaign, Illinois, USA

- Intelligent cognitive systems , 4-5 September 2008, Los Angeles, CA, USA
- InterLink consolidation workshop, Cannes, France, 12-14 November 2008.
- Dissemination event at the FET09 conference, 22 April 2009, Prague , Czech Republic.

The main outcomes of Interlink are detailed in a series of reports, with each of the three thematic areas having produced a 'State of the Art' report and a 'Report on Road-Mapping Research'. These can be downloaded from the InterLink Web site <http://interlink.ics.forth.gr/>.

The results of InterLink are expected to achieve an impact at the following levels:

- A direct impact on science via the creation of networks of skilled researchers, who will elaborate long-term goals and will be prepared to face the associated research challenges within the wider international research community.
- A direct impact on research agendas, via a contribution to building cross-border research agendas in the thematic areas. This will reinforce the visibility of European research efforts worldwide and will strengthen the international collaboration strategy by establishing systematic collaborations with researchers located outside of Europe who will share a common vision of the future for particular domains. It is also anticipated that InterLink will have an indirect impact on European research in ICT, by informing research priorities in FET for FP7 and putting forth views on promising research themes to be considered for inclusion in forthcoming programs of the FET unit of the EC. FET choices will in turn influence the research

- activities carried out at a national level in the EU member states, resulting in a progressive harmonization of national research policies, which is a significant contribution to the ERA.
- An impact on industry: InterLink has increased awareness of IST-related research as a contribution towards ensuring the long-term competitiveness of European industry. Moreover, the project will increase industry awareness of new trends, challenges and visions in IST-related research.
- An indirect impact on research policy development within IST by supplying a vision for implementing research work programmes beyond FP7. Additionally, the project's outcome will also be channelled to policy-making organizations and committees worldwide, through the involvement of their representatives in meetings and workshops.

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The full version of the roadmap for each thematic area can be downloaded from the project Web site at <http://interlink.ics.forth.gr/>

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# Future and Emerging Technologies

**F**uture and Emerging Technologies (FET) is a funding stream in the European Union's ICT Programme specifically dedicated to the promotion and blossoming of groundbreaking ideas and new paradigms for future Information and Communication Technologies (ICT). It supports high-risk collaborative research, specifically in areas lacking an agreed roadmap, where options are unclear or ideas speculative. FET is implemented in two complementary schemes: the open scheme, FET-Open and the FET-Proactive scheme.

Research in FET-Open is motivated by the fast-moving and unpredictable nature of change and innovation in ICT. Here, new and promising ideas – often embryonic, fragile or 'crazy' - are tested and explored. As FET-Open has no predefined work programme, it avoids the risk of tunnel vision in ICT and acts as an early indicator of changing research priorities and new opportunities arising from the latest in science, be it ICT or any other scientific discipline.

The proactive scheme focuses its calls on particularly promising areas with potential for long-term industrial or societal impact. It funds groups of projects that explore a common vision, creating critical mass and the appropriate mix of disciplines to establish a solid scientific basis and substantial results that can drive progress in emerging fields and motivate significant R&D investment later on in the mainstream activities of the ICT programme.

Since new thinking often arises at the crossroads between different scientific disciplines, FET is also the place par excellence for interdisciplinary explorations. Research in FET involves collaboration between different disciplines, including physics, mathematics, chemistry, biology, the life sciences and the arts. Therefore, FET also supports new emerging research communities to

organise themselves, and to align, coordinate and promote their research agendas.

Within this context, the InterLink Coordination Action, <http://interlink.ics.forth.gr/> has gathered an interdisciplinary research community around three areas in which new technologies are likely to emerge in the next 10-20 years, namely Software Intensive Systems and New Computing Paradigms, Ambient Computing and Communication Environments, and Intelligent and Cognitive Systems. These areas are likely to be of fundamental importance for the future development and enhancement of ICTs in Europe. Through a series of international workshops, Interlink has formulated the research priorities that will create the scientific basis for concrete new technologies to be developed in the long run. Its recommendations are based on a sound cross-disciplinary perspective and, importantly, they transcend the European dimension towards global international collaboration.

The kind of work that has been performed within InterLink is important for research funding agencies at all levels to inform their funding strategies and to plan concrete steps in global collaboration schemes, which so far remain all too rare. The visions that are exposed here also vividly show the need to build new bridges across disciplines (for instance in terms of academic structures, research organisation, career perspectives and publication strategies), so that next generations of researchers will be able to evolve their careers in the more challenging, but so much more enriching and rewarding landscape of interdisciplinary work.

<http://www.cordis.lu/ist/fet/>

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## InterLink and the ERCIM Strategy



Keith G. Jeffery,  
President of ERCIM

Following the successful Beyond the Horizon project, ERCIM, with the scientific lead of its member institution ICS-FORTH, proposed to the FET (Future Emerging Technologies) programme and was awarded the Interlink project. Not to be confused with similarly named EC projects on evaluation and environment, this Coordination Action was aimed squarely at advancing knowledge in Europe in three strategic areas identified during the Beyond the Horizon project. These three areas are of critical importance: Software-intensive systems and new computing paradigms; Ambient computing and communication environments; and Intelligent and cognitive systems.

Few would deny that these three topics are of crucial importance to the future of Europe (and beyond). This is confirmed by the explosion in the number of internet connections and devices, the increasing dependence of all sectors of business activity on ICT (Information and Communication Technology), the research frontiers in all disciplines being pushed by advances in ICT, and the social changes caused by ICT. The increased scale of ICT in all dimensions requires that the management of ICT systems be more automated, that interactions between software components, and between those components and humans, be cognitive and semantically rich, and that the ICT systems should be pervasive and continuous. Research in these (and associated) topic areas is thus vital for Europe and - given that resources are necessarily limited - planned research following roadmaps gained by consensus among experts offers the greatest chance of success and return on investment. ERCIM has facilitated such a process in Interlink.

Via its Working Groups and workshops, Interlink has gathered experts from many institutions, and thus represents the consensus view of the community regarding the future of the thematic areas. The Working Group leaders - from ERCIM or ERCIM-associated institutions - have produced excellent reports covering their areas which form a reference framework for the future. The reports contain many exciting challenges for ICT in developing a fruitful environment for the next few decades.

The result of the Interlink project has been to develop a research agenda that will focus European ICT research beyond the i2010 goals and will influence the future of Europe as a knowledge society.





# Software-Intensive Systems and New Computing Paradigms

Information and Communication Technology (ICT) is an important driver of economic progress and economic globalization. Many products, ranging from children's toys to cars or manufacturing plants, and even national and international infrastructure, are inconceivable without sophisticated embedded computers; our daily lives have been transformed by the ubiquitous availability of portable telephones, broadband Internet and ultra-portable netbooks.

Today's systems require a degree of flexibility that can only be controlled by software. Traditional, hardware-based control mechanisms cannot cope with these challenges. As a result, almost every system developed today is software-intensive, meaning systems contain large amounts of software that controls parts of the system or communicates with other systems. Research into software-intensive systems faces challenges of scale, distribution and adaptation that defy traditional systems and software engineering techniques.

## Challenges

Software-intensive systems are characterized by software interacting with other software, systems, devices, sensors and people. Using software to control individual system components and to execute or supervise the overall workflow of a system, offers such significant advantages in flexibility, cost and performance that today almost every system qualifies as software-intensive. Technological progress will lead to further decreases in the cost, power consumption and size of computers and thereby increase the future importance of software-based control. On the other hand, the increasing scale and heterogeneity of systems, the openness and variability of their environments and the increasing incorporation of sensors and actuators are also leading to

a large number of difficulties: current systems are often vulnerable to attacks or fail in unforeseen operating conditions. Systems are expensive to build and many projects are not completed in time and on budget. Changes in requirements often force an expensive redesign and redeployment of the whole system. These challenges need to be addressed.

**Scale:** The most obvious trend in the development of software-intensive systems is the rapidly increasing scale of the systems. This development is driven by the numerous advantages of assembling nodes into systems. This can be demonstrated by comparing a stand-alone computer with a network of computers. In a network, users can access data on other computers and communicate with users on other computers; requests can be distributed to several computers to increase the performance; and the failure of an individual computer does not usually affect our ability to continue working in the network. Thanks to the rapidly shrinking cost, size and energy consumption of traditional hardware components and the emergence of a number of new technologies and paradigms, systems are continuously being scaled up. At the same time, these developments have also revealed that traditional ways of scaling up systems have inherent performance limits.

Another important factor related to scale is the advent of ubiquitous broadband network access and hence geographically dispersed systems. The increasing number of independent nodes and their broad geographic distribution pose a number of problems for the system designer: in a system containing millions of nodes, the failure of individual nodes cannot be seen as an extraordinary event, but rather as a common occurrence. The system has to recognize and compensate for these failures.

Traditional systems often rely on centralized parts to ensure consistency, eg to coordinate transactions or back up data. With increasing distribution, reliance on a central component becomes prohibitively expensive or even impossible. A system consisting of a large number of geographically distributed nodes cannot be stopped in order to update or replace individual components. Instead, updates have to be propagated through the system while it is operating. This means the system must be able to operate in a state which is only locally consistent while preserving overall correctness. This problem becomes even more obvious when there exist components outside the system that are not under the control of the system's designer.

**Heterogeneity:** Technological progress has not only led to more powerful devices, but also to a broad range of devices specialized for different applications or usage scenarios (eg wireless sensors or portable phones). As these devices are integrated into systems, the systems grow increasingly heterogeneous, with the computational power and network bandwidth of different nodes varying by several orders of magnitude.

**Openness and change:** Traditionally the definition of a system boundary, ie clarifying which components are part of the system and must therefore be designed, built and maintained by the system developers, has been an important step in the development of systems. Many of today's systems no longer have clearly defined boundaries, and instead rely on external components for essential parts of their functionality, contain components which are not fully trusted or which have competing interests, and operate in environments which are in large part unknown during the design process.

For example, Web search engines currently index more than a trillion pages: it would be impossible for average system users to operate their own Web search engine with the same coverage. Instead, most systems rely on offers from these companies to perform Internet searches.

The system designer often has only very limited influence on the quality of service of components maintained by external providers.

E-commerce systems for business-to-business transactions are another example: these must constantly adapt to the needs of the market and customers in global enterprises. Traditional systems are not well suited to this kind of change, since they rely on statically connected components with well-defined functionality.

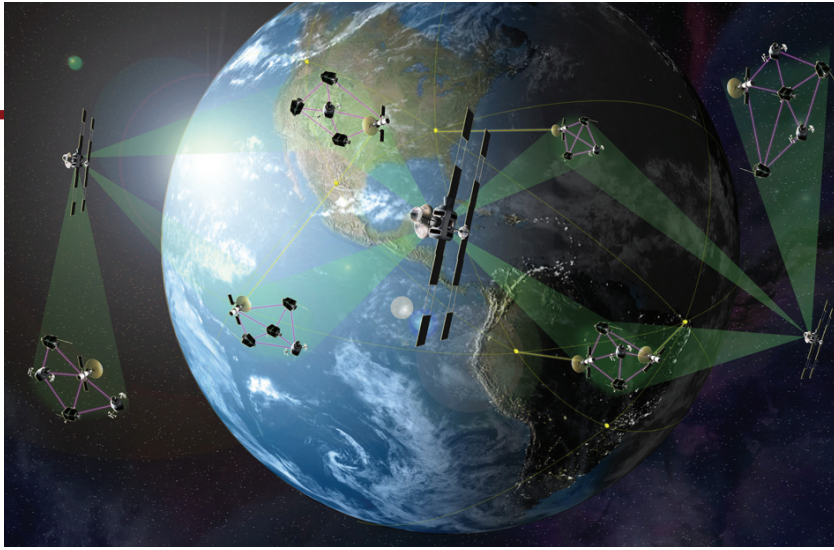
An important goal for future systems is to better support change. In particular, it has to be easy to adapt systems to changing requirements or environmental conditions while the system is running. In many cases the system should even self-adapt if it detects changes in its environment that either derail its current mode of operation or that offer possibilities for improved operation.

**Situation and localization:** With the increasing number of networked embedded controllers and the connection of purely virtual systems to physical devices, 'location' is an important concept. Sensors in wireless sensor networks can normally only communicate with their immediate neighbours and the interpretation of sensor data depends strongly on the location of individual sensors. The emergence of 'location-based services' as a business model also highlights the importance of the location awareness. Examples for location-based services range from simple functionalities such as finding the closest restaurant to complex scenarios such as road billing, fleet scheduling, automotive emergency assistance or infrastructure management. For these applications, the ability to identify the changing positions of individual nodes and to reconfigure the system according to these locations is paramount.

**Resource constraints:** In spite of tremendous increases in the computing power at our disposal, many systems have to deal with resource constraints and trade-offs. Even for purely computational systems, resource minimization is important, since the energy consumption of large net-

A fractionated spacecraft is an example of a Physical Ensemble. Contrary to traditional monolithic approaches, the functionality of a fractionated satellite is distributed across several heterogeneous modules that communicate wirelessly. The image illustrates DARPA's F6 program to design next-generation satellites.

Source: U.S. Defense Advanced Research Projects Agency (DARPA).



works of computers can be staggering. Resource constraints are most pronounced in areas where systems interact with the physical environment. Sensor networks, for example, often have to operate on batteries, and in many scenarios these batteries are difficult to replace after the sensors have been deployed. Reductions in communication overheads or transmission conflicts can therefore have a significant influence on the durability of these sensor networks.

**Data:** As more private and business transactions are conducted online, the amount of data stored, transferred and processed by software-intensive systems is increasing exponentially.

One of the most important technical problems is how to preserve the data and how to use it. The drawback of the information proliferation is that companies and individuals are overwhelmed by all kinds of data: e-mails, business transactions, blogs, forums, instant messaging conversations and more. The problem of the data flood has recently grown more pressing for businesses, because legally they can be held accountable for the quality of their data.

Structured data (especially metadata) such as business transactions or contact details are slowly becoming more standardized, yet the scale of this pales when compared to unstructured data (email text, blogs) and binary data (images, video). Even when data is structured, managing it is still a challenge: Different data formats must be converted; semantics and schemas must be

translated; communities around the data must be considered; and data must be stored (possibly for long periods), maintained and accessed. Privacy also plays a big role, especially in professions that synthesize data from various sources. Examples of such professions are patent attorneys, medical doctors and tax auditors.

## New Research Themes

We have identified two kinds of ensemble that are particularly promising for driving future research: physical ensembles and societal ensembles. Both kinds of ensembles promise to be of great scientific and social relevance.

*Physical ensembles* are intimately connected to the physical world in space and time. They are equipped with sensors and actuators and take into account issues of locality and resource constraints. Examples are real-time embedded systems, modular robots or programmable matter. Coordination in space and time with limited resources is one of the major challenges faced by physical ensembles.

*Societal ensembles* are ensembles that are closely connected to humans, eg smart cities, ambient assistance or global virtual enterprises. Research in this area will have to investigate the dynamics of purposive interactions and how the structure of evolving societal interactions can be

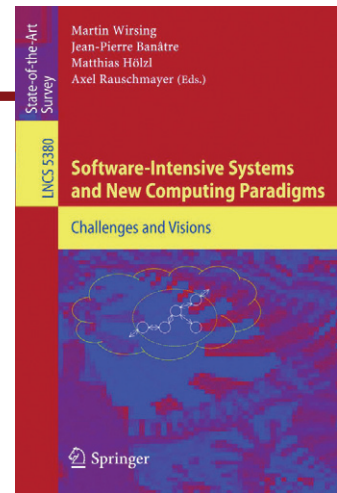
reflected in the architecture and the design of the software. Evolution of societal ensembles will be a long-term process that goes beyond single-run adaptation, and systems must be able to maintain societal coherence while supporting diversity and context awareness.

The main challenge of ensemble engineering may be expressed as harnessing the massive scale, stochastic behaviour and adaptation of ensembles. The large number of nodes in an ensemble and the open and non-deterministic environment in which it operates make it difficult to design the behaviour of the ensemble using conventional engineering methods. Current techniques of system and software engineering are woefully inadequate for designing future ensembles. Since the different challenges interact in non-trivial ways, we consider it important to focus research on approaches which address a broad range of issues: harnessing parallelism; designing unconventional models; dealing with component failure; the problem of time and distribution; data storage and preservation; and dynamic complexity.

Because current development tools and languages are not well suited to ensemble engineering, research efforts should also include development tools and languages such as the development of introspective and reflective systems; contextual reflection; efficient run-time analysis and detection of system properties; and support for autonomous system evolution and model-centric development. To support the ensemble engineer throughout the development process, research in the areas of formal methods for specifying and analysing system properties, development tools and development processes is also necessary.

## Conclusion

Software-intensive systems already have a strong influence on economic and social developments throughout the world. Given the advantages of software for controlling systems and the decreasing cost of controllers, the importance of



*“Software-Intensive Systems and New Computing Paradigms – Challenges and Visions”, edited by Martin Wirsing, Jean-Pierre Banâtre, Matthias Hözl and Axel Rauschmayer, published by Springer in the “Lecture Notes in Computer Science” series vol. 5380, presents in depth the results of the INTERLINK Working Group on Software-Intensive systems and novel computing paradigms.*

software-intensive systems will doubtless increase in future years. Continuing future research efforts are needed for Europe to stay competitive and to ensure that the needs of the European society are met by future developments. Ensembles are likely to become a crucial area for new research and future development. The trend to this kind of system is already evident in the software-intensive systems currently being developed or deployed. However, we still need to address the inherent complexity of ensembles, to ensure their trustworthiness, security and reliability and to ensure that they can be engineered cost-effectively.

The scope of the research tasks and their importance to the future of European and international society are compelling reasons for the research to transcend national boundaries and for research projects to be undertaken on a European level. Interlink believes that it is advisable wherever possible to further accelerate these research efforts, to share knowledge and expertise with non-European countries, and to distribute the significant financial burden of the necessary research and international cooperation beyond the boundaries of the European Union.

# Intelligent and Cognitive Systems

Successful attempts at building artificial intelligent cognitive systems are still mostly restricted to systems designed for ‘sunshine’ environments with limited scope and simple tasks. At present, it is still impossible to transfer the developed skills and abilities to varying contexts and tasks without the need for costly redesign. In the future, research efforts must be devoted to rich cognitive challenges which are measurable and scalable in open-ended scenarios under changing conditions, and to the development of measures, metrics and benchmarks that highlight and focus on both transferability and performance.

An encouraging spectrum of 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 dialogues, handling of few objects).

Technological progress in the fields of computational power, mechatronics and sensor systems is allowing 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, which will address one of the key emerging challenges of human participation in the ‘Information Society’, namely the information overflow problem. Truly intelligent cognitive systems should be able to operate in an autonomous way, naturally interact with the world and with people, and be (self-)adaptive to changing situations and contexts, including the user’s preferences and needs.

## Challenges

The challenges we face in the building of intelligent cognitive systems can be summarized as follows:

- Methodologies supporting the development of systems that explore their own sensorimotor primitives, body morphology, the environment

and their effective interaction with it. Systems must be able to predict body dynamics and the physics of the world and, thus, develop an ability to reason about it.

- Methodologies supporting the learning of new skills, adaptation of existing skills and the ability to switch between different learning modalities. We must allow for multiple forms of learning to be combined, as well as context-dependent switching between those forms of learning. The relevant 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.
- Methodologies supporting learning, recognition and classification of objects and events (eg associative memories, stochastic computing etc).
- Technology for soft sensors, massive connections and 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 allow researchers from different fields to evaluate their theories and simultaneously provide a framework for the benchmarking of different algorithms (a fundamental and difficult issue).

## New Research Themes

A new approach is needed to cognitive system development. Instead of focusing on system

development, we must 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 with other agents. Several key research clusters are proposed to structure the processes for understanding natural cognition and for engineering of cognitive systems.

#### **Processes and representations for emergence (system internal view)**

An important aspect for future cognitive systems is the definition of morphogenetic processes (processes that cause an organism to develop its shape) for information processing. This takes into account cooperation, stabilization, consolidation, focusing, categorization and mode selection.

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 sensorimotor experiences can be organized into appropriate data structures that allow sensorimotor learning at different levels of abstraction. Sensorimotor knowledge is gained by humans from childhood on, when children start to 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. In parallel to the development of motor capabilities, the processing of sensory data also gradually improves. The visual system is an example, which through time enhances its discrimination capabilities as well as the perceived spatial resolution.

In addition to studying processes and representations for emergence, it is necessary to investigate the building of integrative cognitive system architectures, which should provide a framework for modelling, validation and the benchmarking of cognitive systems.

#### **Emergent cooperation (system external view)**

Cooperation between agents must be based on the principles of alignment, entrainment, imitation, sharing, anticipation and proactive interaction. Guiding 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, robot-robot and other forms of interaction.

The field of Human-Machine Interaction has received growing attention in the recent years.

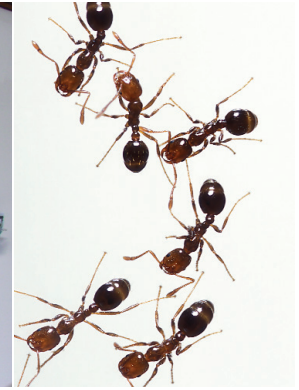
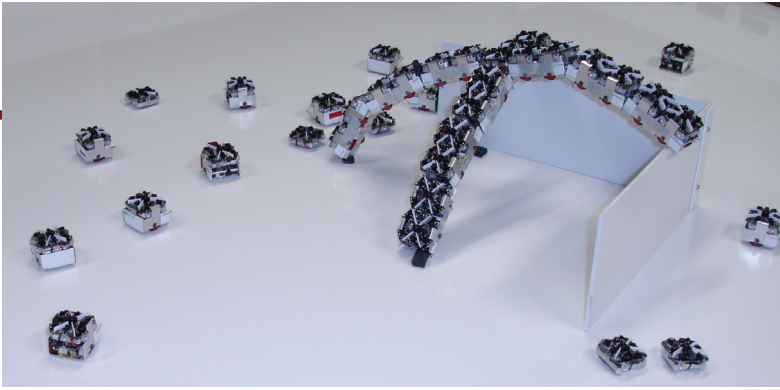
The goal is to develop autonomous, interactive agents that operate within human environments and play a beneficial role in the daily lives of people. A key aspect in this field is multimodal interface technology, which allows humans and their environments to be 'observed' by recruiting signals from multiple audio-visual sensors. In the context of human-robot interaction, a fundamental issue is that of natural multimodal interaction, which is based on vision for person localization and tracking, gesture and posture recognition, speech recognition, and dialogue processing..

#### **Embodiment for guiding design (system basis and frameworks view)**

The development and emergence of cognition relies on artificial embodiments having rich perceptual and motor capabilities. Biologically inspired artificial (robot) systems with such capabilities therefore represent the most suitable experimental platform for studying cognition.

Body morphology of artificial cognitive systems should be inspired by biological systems, and the cognitive system should be able to learn its own body schema and cope with morphological changes arising through physical interaction with the environment. The following technologies need to be further developed to achieve these goals: artificial skin, soft and compliant mechanisms, new sensors, new energy-efficient actuation methods and on-chip multi-core systems.

Humanoid Personal Robots is an example of an artificial cognitive system, and a key growth



Robot ensembles or “swarm robots” dynamically aggregate into a symbiotic organism (picture left: University of Stuttgart). The big challenge is to capture principles of collective operation, such as altruistic cooperation, dynamic division of labor, and emerging communication, as for example in ant colonies, which 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.

industry of the 21st century. The big challenge is the advancement of robotic technology to the point where interactions between humans and robots run smoothly and robots are able to fulfill roles in the human living space. In recent years there have been renewed efforts to develop humanoid robots that perceive, move and perform actions but successful attempts in this area are still limited to simple scenarios.

The design of such systems requires coordinated research efforts that span a wide range of disciplines, such as learning theory, control theory, artificial intelligence, human-machine-interaction, mechatronics, perception (both computational and psychological), biomechanics and computational neuroscience.

The challenges for the development of humanoid robots also hold for robot ensembles. The vision of multiple, inexpensive robots operating in concert to solve complex and dynamically changing tasks has not yet been achieved. From a scientific/technological perspective, the two major challenges consists of (i) developing efficient and general models of collective operation; and (ii) conceiving hardware for disposable and collective operation.

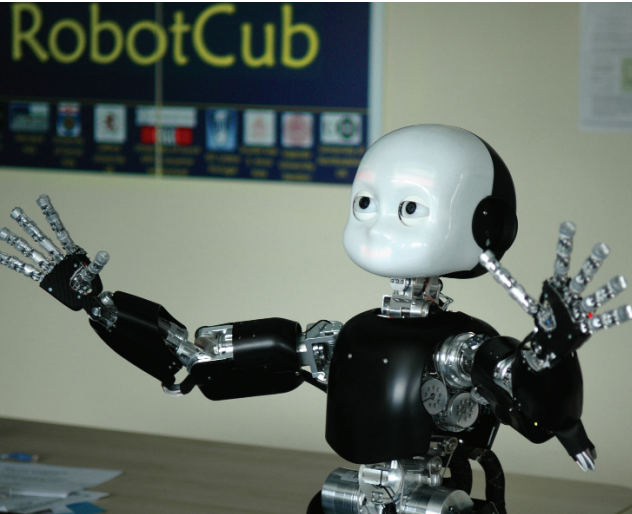
Although many models of collective operation (swarm intelligence) exist, they tend to be applicable only to specific robotic hardware and tasks. The big challenge is to capture principles of collective operation, such as altruistic cooperation, dynamic division of labour and emerging communication that are applicable to a wide set of robot-

ic platforms and tasks. Existing models in the biological literature are not easily applicable to a real robot. For example, a model often used to explain division of labour 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; and at the same time are general enough to be easily applicable to novel platforms.

Most robots for collective operation are realized using the same design principles as 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 complicated 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. It is 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.

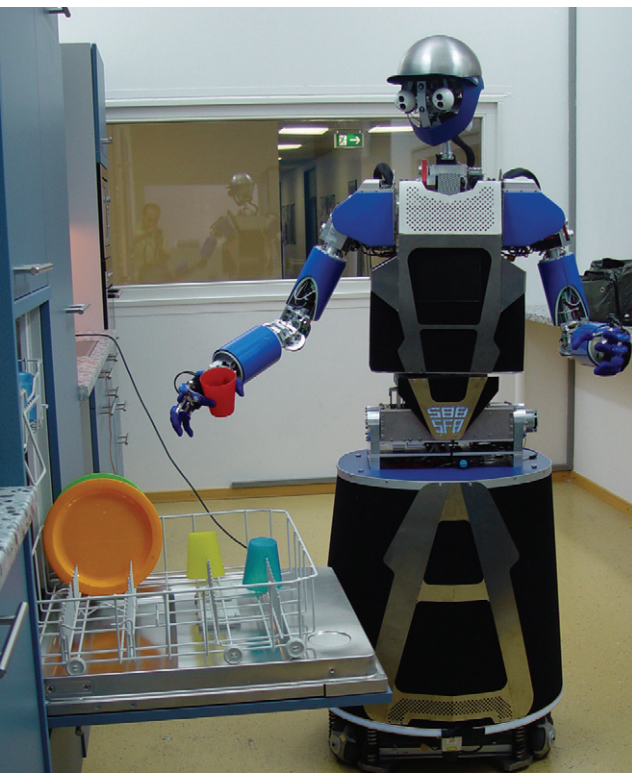
### **Principled benchmarks (system evaluation view)**

Evaluation scenarios for emergent design should go beyond task orientation to consider satisficing instead of optimization and emergence of



iCub, an advanced humanoid robot developed by the European Project RobotCub to support community research on embodied cognition. iCub is a full-fledged humanoid robot “child” with sophisticated motor skills and several sources of sensory information including vision, sound, touch, proprioception, and vestibular. Picture: robotcub.org.

The ARMAR humanoid robot, developed at Karlsruhe University. ARMAR has been built to act in human-centered environments and to serve as assistant and companion of humans in daily life.



competence in different environments. Child development stages can serve as guides for the development of artificial cognitive systems and as principled benchmarks with which to evaluate the growth of the system.

Compared to humans or primates, the ability of today’s robotic grippers and hands is surprisingly limited and their dexterity cannot compare to the capabilities of the human hand. Contemporary robotic hands can grasp only a few objects in constricted poses using limited grasping postures and positions.

Although there is an abundance of artificial hand designs ranging from one to eighteen degrees of freedom, replicating the effectiveness and flexibility of human hands in object manipulation tasks undoubtedly requires a fundamental rethinking 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, and neuroscientists and cognitive scientists are building models of how the 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.

### **Integrative Studies of Cognitive Systems**

In recent 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 to fit the different results together to achieve complete processing models and an integrated system architecture. Progress can only be made through intensive dialogue between researchers from the fields of natural and artificial cognitive systems.



# Ambient Computing and Communication Environments

Computing devices have now pervaded everyday objects in such a way that users no longer notice them as separate entities. This trend towards the 'disappearing computer' extends beyond homes, offices and leisure environments and will include all kinds of buildings, places and roads, constituting complete cities that embody invisible information and communication systems. They will interact with multiple users, thus creating rich socio-economic systems with the potential to radically change not only how we perceive, create, think, interact, behave and socialize as human beings, but also how we learn, work and live, as individuals or in societal settings.

Our evolution towards a future information and knowledge society is characterized by the development of personalized individual as well as collective services that exploit new types of infrastructures and components situated in smart environments. These are based on a range of ubiquitous and pervasive communication networks that provide ambient computing and communication at multiple levels. The collective services are provided by a very large number of 'invisibly' small computing components embedded into our environment. They will be 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 and leisure environments, providing the raw data (and active responses) needed for a wide range of smart services. Furthermore, new and innovative interaction techniques are being provided that integrate tangible and mixed reality interaction. In this way, the usage and interaction experience of users is expected to be more holistic and intuitive than today. It is anticipated that economics will drive this technology to evolve from a large variety of specialized components to a small number of universal, extremely small and low-cost components that can be embedded in a variety of materials.

## Challenges

While the area of ambient computing and communication environments is clearly facing a large number of challenges, we address here two grand themes that were identified by InterLink as being of major relevance.

### **Socially aware ambient intelligence**

Socially aware people are community minded and active in their social context.

Communication between humans as part of a more comprehensive social dialogue can also involve different artefacts as part of a socially aware system. Whereas embedded sensors and devices are already common in today's environments, the future challenge is the creation of 'intelligent' or 'smart' environments which behave in an attentive, adaptive and active way to provide specific services in these environments.

Applications and services will behave in a 'socially aware' way. This means that they will provide a sense of involvement and knowledge about the social behaviour of other persons, such as their degree of attention, desire for customization and control, their emotional state, interests and their desire to engage in social interactions. Socially aware ambient environments will be composed of a collection of smart artefacts that understand social signalling and social context, resulting in the ability to improve social orientation and collective decision-making. Research challenges and requirements for socially aware ambient systems include:

- to build systems that understand social signalling and social context
- to provide people with smart tools to make informed and mature decisions, rather than having fully automated systems
- to improve collective decision-making
- to provide infrastructures that enable inter-communication of a wide range of devices, sensors, actuators and a functional coordina-

tion and intelligent scheduling in a self-organizing fashion

- to integrate reflexive systems for semantic interpretation of contexts, user preferences and profiles
- to extend group-oriented interfaces: from single users to groups and teams and communities
- to consider the triangle of multiple devices, multiple people and multiple contexts.

### **Privacy, trust and identity**

In today's connected world, where computers frequently mediate our interaction and communication with our family, friends and the outside world, many people suffer from the 'Big Brother' syndrome. Privacy in particular is an elusive concept, not least because everyone's sense of privacy is different. Moreover, the notion of privacy is unstable, because people's perception of privacy is situation-specific, or more generally, context-dependent. People's expectations of privacy may differ according to many factors and situations.

The issues of changing views on privacy, trust and identity are mainly a result of creating 'smart' devices. It is now obvious that there is an interaction and a trade-off between on the one hand providing intelligent support with tailored functionality via the collection and interpretation of sensor data, and on the other respecting the right of people to control which data are collected, where, when, by whom and how they are used.

There is the danger that we are moving from a situation where people considered privacy to be a legal and moral right (and sometimes a socially negotiated feature) to a situation where it becomes a commodity to be traded or paid for, and thus a privilege for those who can afford it.

Research challenges and requirements for Privacy Enhancing Technologies (PETs) include:

- to overcome the privacy/trust/security concerns of people by initiating an open dialogue and making available information about system design decisions. The question of why

data are collected is increasingly the focus of attention.

- to address the conflict of ubiquitous and unobtrusive data collection/provision with human control and attention in an open fashion, and to make it part of system design
- to build and integrate privacy-enhancing technologies (PETs) that respect the moral and legal rights of people in current and future sensor-enriched ambient environments
- to explore existing solutions in this area as interrelated and even competing issues, and to move beyond this to address necessary safeguards in an upcoming world of ambient intelligence, where basic criteria identified in network applications, such as anonymity, pseudonymity, unlinkability and unobservability are difficult to achieve.

## **Twelve Research Lines**

Based on the issues emerging in this thematic area, and in order to identify more specific recommendations for future research agendas, a set of scenarios was developed. Due to the pressing problems of current and future cities and metropolitan areas, 'urban life management' was identified as the overall umbrella scenario. A more detailed rationale and description of this is provided in the next article entitled 'The Humane City', providing a vision for urban living in the city of the future that is based on the notion of smart and hybrid cities. As a result of several workshops, twelve research lines have been identified, ranging from global issues to more 'horizontal' aspects that are also relevant cross-thematically.

### **1. Rationale for the humane city**

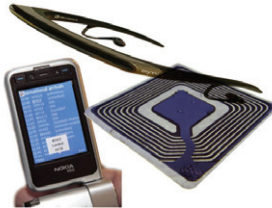
The extension and transformation of smart cities towards 'humane cities' involves democratic, emotional and seemingly irrational aspects of our everyday life. It is important to form a solid theoretical basis for these aspects of human activity that are carried out in the complex net-



*Multiple People*

Limitations and challenges were especially identified for the extension of traditional ambient and ubiquitous computing environments, ie the need to move from one person and multiple devices to multiple people and multiple devices in multiple contexts, either social or physical (locations/spaces).

*Multiple Devices*



*Multiple Contexts*



work of artefacts and environments. A theoretical foundation of what constitutes a humane city is required in order to provide an orientation for the role that Ambient Intelligence (Aml) can and will play in the future. Aml is about smart, adaptive environments reacting to people and objects. Thus, it is important to reflect on the range of interactions between people and their environments in order to determine how Aml can contribute to enhanced efficiency, increased creativity, and increased well-being in a humane city.

## **2. Implicit versus explicit Interaction and tangible interaction**

There are a number of key differences between interaction with a traditional desktop or mobile phone interface and interaction in an Aml environment. One important aspect is the need to support both explicit and implicit interaction, their coherent coexistence and a smooth transition between them. Sensing and recognition technologies provide environments with implicit communication originating from highly distributed devices. The challenge is to provide transparent relationships between input and output and to coordinate across many output locations and modalities without overwhelming the limited attention spans of people. The 'tangible interaction' approach is especially suited for this, allow-

ing the user to interact with an Aml environment by manipulating the environment itself.

## **3. Hybrid symmetric interaction**

Users' actions in real and virtual environments are often neither consistent nor can they be considered symmetric or reciprocal. These aspects become particularly important for hybrid environments in which no particular environment/world prevails. Usually, consistency is achieved when users explicitly update information in one or multiple virtual environments according to changes in the real world. For example, when moving a real paper document from the desktop into the bin, the representation of the document in the virtual environment is also deleted. It is conceivable that sensors and mechanisms can maintain this sort of consistency between actions in real and virtual environments. Through the recent deployment of sensors in physical environments, changes in the latter can easily be reflected in the virtual environment. For example, the GPS-measured locations of vehicles in a public transportation network can easily be recorded and visualized in a virtual representation of geographic space (eg in Google Earth). More complicated, however, is the other direction: changing physical states due to virtual sensor measurements or virtual actions. One

could imagine that by indicating destinations in the virtual, passengers could influence the route that public transportation vehicles (even autonomous ones) take in the real world. This research line focuses on maintaining consistency of the representation, no matter the environment in which the action takes place.

#### **4. Space-time dispersed interfaces**

The humane city requires the exploration of novel user interfaces that might be dispersed not only in space, but also in time. This research focuses on the ways in which humans can interact in time and space through and with computing machinery. The humane city requires that meaningful geographic scales for inhabitants be taken into account. If citizens are moving through the city, these options need to be changed on the fly. Because not only absolute geographical space matters, information should follow users along their trajectory through space. To realize this vision, dynamic scheduling concepts need to be developed taking the full range of the space-time continuum into account. A related aspect is to investigate the time persistence of different city interfaces that support social interaction: those that last for a long time (historical records) and those that are very volatile (spontaneous encounter of two people).

#### **5. Crowd and swarm-based interaction**

Recent developments in social software applications show how very large groups of users can interact and communicate through Internet-based applications. However, the synchronous and spontaneous interaction of larger groups, especially when co-located in a small area (eg a soccer stadium), has just begun to be addressed in simple applications, such as SMS-based voting systems, GPS-based urban games or artistic exhibits. The particular focus of this research line is to investigate the role of smart public, urban spaces in supporting large group interactions. Large groups or crowds consist of hundreds or thousands of individuals in the same place and engaged in similar activities. There are a myriad

of possible concurrent and real-time interactions that a crowd can engage in. Complex behaviour emerges and dynamic social interactions similar to those of 'swarms' can take place. It is obvious that this requires a complete rethinking of the interactions of multiple users and multiple devices.

#### **6. Spatial and embodied smartness: smart spaces as distributed cognitive systems**

This research line deals with 'smart spaces' considered as a compound physical agent that acquires data from its environment through sensors and acts upon it via actuators. Contrary to a 'classical robot' that operates towards its outside, the cognitive capabilities of a smart space can be considered as an 'outside-in' robot, where the human user is an element of the internal environment of the smart space. As smart spaces scale up, they may also comprise nested smart spaces, such as a smart building composed of several smart rooms. In this context, an emerging research issue is achieving seamless and coherent 'smartness' among connected heterogeneous spaces of different scales that form complex patterns. Moving towards these complex entities requires new perspectives, eg the notion of 'smart skins' as an implication of sensors and actuators being distributed on the inner and outer surfaces of these entities.

#### **7. Awareness and feedback technologies**

Awareness and feedback technologies (AFTs) encompass the solutions that contribute to a high degree of coupling between human users and their environments. This requires mutual knowledge of the internal status of the different parts of the coupled system. AFTs are able to infer psychological, cognitive, and social states of individuals and groups (examples are attention, stress, anxiety, relaxation or concentration), take those states into account, and provide feedback (positive or negative) to the individual or collective users. The goals of this research line are (i) to keep the human in the loop in all possible situations by moving away from fully automated sys-

tems and facilitating mature decision making and informed action; and (ii) to design and build computing infrastructures that enable intercommunication for a wide range of devices, sensors and actuators combined with functional coordination and intelligent scheduling in a self-organizing fashion.

### **8. Emotion processing**

Technological advances in pervasive computing and ambient intelligence have created technology-rich environments but failed to address emotions. Research towards

‘emotion processing’ which gives at least an approximate abstraction of the principles of how humans perceive, experience and act emotionally, provides the potential for a whole new era of ambient intelligence. Research questions could address issues such as the mechanisms of sensing, recognizing and representing emotional states, together with modelling, abstracting and representing experience. The goals include (i) the sharing of emotional experience, thus mediating human-to-human emotional expression over distances; (ii) the evolution of emotional digital artefacts resulting in emotional behaviour of electronic devices; and (iii) emotional adaptivity.

### **9. Social networks and collective intelligence**

Social relations and networks deeply influence everyday experiences in global cities. However, today’s computer systems are not fully aware of social networks in a city, and are unable to effectively support various urban activities. One reason is the lack of appropriate basic sensor data; another is the lack of tools for exploiting these data. In this research line, a number of topics relating to collective intelligence must be explored, including social networking tools for creating it, methods for evaluating it, the role of communications networks in creating it, collaboration tools for collective intelligence and decision making, and understanding the impact of collective intelligence on urban life.

### **10. Self-organization in socially aware ambient systems**

Future computing systems will be highly distributed and will consist of numerous networked devices of different scales, resources and capabilities. Consequently, services and functions have to be composed ad hoc in a self-organized fashion and adapted with respect to limited resources, but also adapted to local and global situations and/or environmental needs. Beyond the general research challenges and requirements listed before, we add here technical challenges that must be solved when creating substantial ambient environments:

- establishing self-organization of a multiplicity of resource-limited devices within permanently changing device and environment conditions
- establishing self-organization of a multiplicity of service providers and consumers with respect to content delivery reliability
- establishing configuration tools for adaptation of device ensemble behaviour within rapidly changing device environments and device conditions.

### **11. Realization and user experience of privacy and trust**

This research line has its origin in the conflict of data provision with human control and attention. Issues like privacy, trust and identity raise not only technical, but also social and ethical problems, particularly with regard to legal and moral rights. Many aspects of ambient intelligence are relevant here, particularly identifying which information is valuable to whom, and how, when and from whom it is secured. In this effort, social sciences research will have to augment known cryptographic approaches to security. Due to the complexity of the issues, only a few specific questions are mentioned here: “Will limiting recording be part of improving privacy?”, “Will destroying data improve privacy?” “Are there ways to keep information contained?” and above all, “Which new notions of privacy have to be defined?”. These questions will trigger a wide range of future research activities.

## ***12. The scaling issue***

Ambient spaces originate in physical places but feature multiple ambient intelligent services. The scaling factor can range from a body to a room, a building, public space, neighbourhood, city, region or country. It can grow according to how complex it is due to the huge number of functionalities it will provide. The scaling of ambient intelligent spaces is not a straightforward or trivial task. A range of problems arises when moving beyond the more or less well-defined and constrained realm of personal spaces, such as rooms, flats and homes. Some of the related problems include:

- fuzziness of smart space boundaries: one person's 'neighbourhood' for example, may be totally different to that of their neighbour.
- conflicts of interest among Aml spaces: As we move from smaller to larger spaces, the number of people and Aml resources residing in them increases, and people do not always have common goals or intentions. In addition, it is very likely that different Aml environments will also have different goals. This means that conflicts will inevitably arise.
- availability, ownership and use of resources: environments of different size and scope require some kind of seamless integration among private and public resources.

In order to reach satisfying answers to these research challenges, they have to be seen in the context of a variety of application areas. While urban life management in contemporary and future cities is our umbrella scenario for creating 'humane cities', we must tackle subsets of this overall theme such as smart transportation, healthcare with extensions to ambient assisted living, and responsible citizenship (with interesting aspects of cultural differences and different social contexts).

# “The Humane City”

## – An umbrella scenario of “urban life management”

As mentioned in the previous article, ‘Ambient Computing and Communication Environments’, during the Interlink project, a cross-thematic umbrella scenario was elaborated for guiding the development of future research agendas. The notion of the ‘humane city’ serves as a vision for the ‘city of the future’ and for the future of urban living. The humane city should be a city in which people enjoy everyday life and work, and have multiple opportunities to exploit their human potential and to lead a creative life. The important question was, and of course still is: “How can information and communication technology – in particular ambient intelligence – support people so that their urban space represents itself as a humane city?”

The starting point is to supply infrastructure for communication, allowing vast numbers of people to easily share information, exchange opinions, have discussions and reach mutual understandings/agreements through their communication. However, at the same time as providing complete freedom to access any type of information, it is necessary to strictly protect personal security and privacy so that people can trust each other and the integrity of the basic infrastructure and the services provided by a range of different service providers. In the work and business context, infrastructures and services should support any type of workplace design, buildings, and multiple forms and modes of work and collaboration for individuals, groups, teams and organizations.

While the notion of the humane city includes requirements for communication, interaction, collaboration and social networking opportunities, one also has to look at the technical aspects of its realization. The development from an ‘ordinary’ city to a ‘humane’ city can be summarized by the following progression:

- the first step was and is the extension of the real city into the virtual world. We call the integration of complementary real and virtual parts the ‘hybrid city’
- the second step is the transformation of services that are currently available in our cities into smart services and thus the city into a ‘smart city’
- the third step is to adopt certain requirements so as to avoid the creation of a technocratic smart city that monitors and controls its citizens in the interests of only a few stakeholders. The realization of a humane city should provide opportunities to keep citizens ‘in the loop’, informing them of decisions, empowering them and providing socially aware smart environments in which privacy and trust are respected and provide the basis for fostering a creative, all-inclusive and humane society with a high quality of life.

In order to make this umbrella scenario more concrete, we have to identify examples of potential future environments and services. We can then make proposals for the corresponding infrastructures, detailing the technical paradigms and applications built on top of them and the social rules and mechanisms that will help organize and manage life in the future city. Here are three selected example scenarios:

### Smart transportation

Travellers in smart cities will have transportation information constantly at their fingertips. They will be able to query means of transport, locations and schedules, timetable changes and alternatives that are either cheaper and/or faster. Furthermore, the information provided by the system will take into account current traffic conditions and the trip’s impact on the environment. Every object taking part in the complete transportation process (eg humans, vehicles, roads, bridges, signs etc) are considered to be

both sources and sinks of information. Ambient information and interaction provision will be central to this process.

### **Health monitoring and medical therapy**

Doctors and medical staff will be able to gather information about a patient's medical conditions, including medical history, nutrition habits, family situation etc. Comprehensive and intelligent use of this information will allow integrated medical diagnosis and therapy to occur – in emergency situations as well as in routine practice - that will dramatically change peoples' health, social inclusion and personal attitudes. Awareness and feedback technologies play an important role in this.

### **Responsible citizenship: facilitating engagement and involvement**

People will be encouraged to play an active part in their humane cities society by being offered a variety of forms of social participation. This includes standard forms of leisure proposals (eg recommendations for museum, theatre and exhibitions that fit individual personal interests). The information can be also shared by people who don't know each other but who could take the role of companions. It also includes more advanced proposals that involve contributing to the community and taking part in social activities. This kind of participation will be available everywhere and at any time, in order that opportunities for social inclusion and involvement may be offered continuously and in an informal and ad hoc way.

The challenges we face in developing humane cities confront us at various levels. One way of investigating them is to state our overall goals for designing a humane city:

- to enable the development of a humane and creative society
- to facilitate social interaction and communication
- to foster individual and social creativity and collaboration

- to facilitate social networks in real and virtual spaces
- to facilitate personal expression and social experiences
- to address emotional and affective aspects
- to address and involve all our human senses
- to keep the human in the loop
- to assure privacy and trust.

On this basis, more specific goals and proposals for future research agendas can be developed depending on the scientific domain under consideration. One example was provided in the previous chapter, which identified twelve research lines for the thematic area of Ambient Computing and Communication Environments.

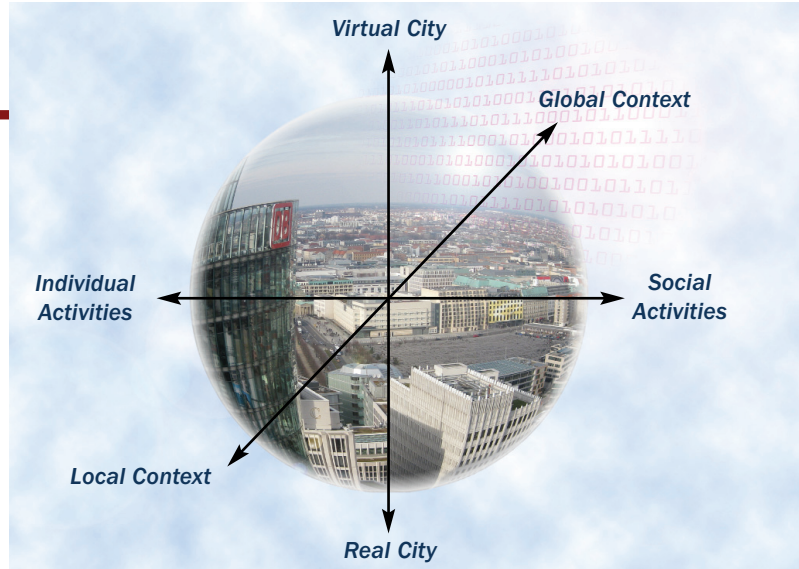
## **Cross-thematic synergies**

The umbrella scenario of 'urban life management' and the vision of the 'humane city' imply many interdisciplinary aspects resulting in common themes to be addressed by all three thematic areas of InterLink. We list some thematic examples that provide opportunities of creating cross-thematic synergies between the three InterLink areas 'Ambient Computing and Communication Environments', 'Intelligent and Cognitive Systems', and 'Software-intensive Systems and New Computing Paradigms'.

### **Hybrid nature and symmetric interaction**

The increasing 'physicality' and hybrid nature (eg via augmented reality) of ambient environments implies a strong relationship of ambient computing and robotic systems. Smart spaces can be understood as distributed cognitive systems. Contrary to a 'classical robot' that operates towards its outside, the cognitive capabilities of a smart space can be considered as an 'outside-in' robot, where the human user is an element of the internal environment of the smart space. From another perspective, 'robots' could be understood as physical 'avatars' in the real world representing digital actors in the virtual world. In





Key Dimensions of Humane Cities (there are more but not depicted here): A Hybrid City consists of a real city with its physical entities and real inhabitants and a parallel virtual city of counterparts of all real entities and people. The parallel virtual city will not be a complete model of the real city. It will be, on the one hand, only a reduced model and, on the other hand, it will contain additional information not readily available in the real world or entities that are different from or do not “exist” in the real world. Thus, we can state that there will be a continuous dimension with “real” and “virtual” as its end points.

the ‘hybrid city’ approach - constituted by a real city with its physical entities and real inhabitants and a parallel virtual city - it should be possible that the reaction/motion part of applications realized in the real world could be triggered by events/actions in the virtual world. Equally, a mediated reaction in the real world could be still triggered by (human) actions in the real world. The challenge is now that both forms of initiating actions and transformations in the real world are possible, can be treated in a similar fashion, and provide appropriate interaction options for the humans.

### Sensors and actuators

There are particular topics of common interest in the area of sensors and actuators. In the envisioned combined ‘sensor-actuator’ systems, sensors will go beyond the simple identification of objects provided by today’s technology (eg RFID tags). Sensor nodes must know their own local and global positioning and their integration in large-scale networks (see also complexity and scaling), and they should be aware of their

absolute and relative proximity. In many cases, sensors are deeply embedded in the substrate of the ambient environment. This requires new considerations with respect to maintenance, including energy efficiency issues because replacement of highly integrated components is not feasible. Actuators are frequently used as mechanisms to introduce motions in the real world which again relates to the theme of symmetric interaction mentioned above.

### Artificial intelligence and human in the loop

Ambient intelligence (Aml) deals with a new world of ubiquitous computing devices, where physical environments interact in various ways unobtrusively with people and vice versa. In order to make the reactions of the system ‘intelligent’, it is necessary to interpret the (sensor) data being collected and aggregated in a sophisticated way. There is a large body of research on methods in the artificial intelligence domain already existing or being developed, e.g., spatial and temporal reasoning that is well worth of being exploited. The results can improve the

‘intelligence’ component of Aml environments, providing better support for humans and access to essential knowledge in order to make better (ie. more mature and informed) decisions when interacting with these environments. At the same time, one has to avoid fully automatic and automatic approaches by providing interaction options in order to keep the human in the loop.

### **Complexity and scaling**

The complexity and scaling issues of Aml environments require new computing paradigms and software layers that facilitate communication between (physical) human-environment interactions and the underlying infrastructure. The complexity of the ambient computing world also increases dramatically when devices and components originating from differing application contexts must suddenly start to work together. Future software-intensive systems will not only feature massive numbers of nodes per system, they will also have to operate in open, non-deterministic environments interacting with humans or other software-intensive systems. This future generation of software-intensive systems can be called ‘ensembles’. These ensembles need a distributed software infrastructure that allows a dynamic orchestration of devices realizing self-organized communication and cooperation of autonomous device entities. Future software-intensive systems are therefore essential for building up a basis for ambient computing and communication environments, and must achieve the following requirements:

- **Composability:** to provide a framework that supports the smooth integration and reuse of independently developed components
- **Dependability and security:** to provide a generic framework that supports safe, secure, maintainable, reliable and timely system services
- **High-performance embedded computing:** an increase of several orders of magnitude in computing densities will be crucial to achieving the goals of Ambient Intelligence
- **Interfacing to the environment:** to provide new ways of interfacing with the natural and man-

made environments, and in particular more intuitive ways for humans to interact with technical systems.

Future generations of software-intensive systems can help in realizing the vision of a humane city in which people enjoy everyday life and work, have multiple opportunities to exploit their human potential and lead a creative life.



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