UBIQUITOUS COMPUTING AND NEW FRONTIERS OF AUTOMATION

Wilhelm Bruns

Bremen University, Germany
Research Center for Work, Environment and Technology (artec)
bruns@artec.uni-bremen.de

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Abstract: *Ubiquitous Computing*, a vision of invisible computing integrated in our everyday surroundings, first introduced by M. Weiser and his group at Xerox PARC in 1988, is still in its early infancy and far from leaving the laboratory stage. Nevertheless there are foreseeable applications in specific areas like automotive automation, health care, home automation, advanced manufacturing. Some aspects of *Ubiquitous Computing* from an automatic control perspective and its relation to mixed reality, augmented reality and pervasive computing will be covered. Several problems like geometric representation, extensible computing, scalability, movable interactions, integration of various network-technologies, user interface design for multi-modality, design methodologies and evaluation techniques, security/privacy issues and enabling software concepts are touched and it will be speculated about how Ubiquitous Computing might influence Low Cost Advanced Manufacturing and how experiences from the automation and control field might influence the emerging community.

Keywords: ubiquitous computing, intelligent environments, invisible computing, pervasive computing

Endlich sind alle Glühbirnen auf Erden miteinander verbunden.
Die Vorstellungswelt des Paranoikers, seit jeher beherrscht von universeller Vernetzung,
liegt uns nun vor als Spielfeld.
Seine Software erwies sich als die vorteilhafteste Investition in die Zukunft
Nun ist seine Welt nicht mehr vorstellbar
Und wir alle befinden uns auf der Suche nach einer neuen Irrealität
Der Geist arbeitet auf der Höhe seines Könnensbewusstseins
Halb Chip, halb Tiefe

Botho Strauß (1999)

Finally all electric bulbs are connected.
The imagination of the paranoid, at all times governed by universal networking,
now lies in front of us as a playground
His software proved to be the most advantageous investment into the future.
Now his world is not imaginable any more
and we all find ourselves on a search for a new unreality.
The mind is working on the summit of its consciousness of ability
Half chip - half depth

(Translation by WB)

1. INTRODUCTION

The above text of a famous dramatist of German language has been used as an entrance to a theatre performance *Theatre of the Machines* presented by a Bremen project of computer science students at the International Theatre Festival in Stuttgart-Germany. The main focus was on the question: who is controlling whom in a networked world of computers, marionettes, avatars, robots, sensors and a musician (Fig. 1).

Ubiquitous Computing or computing presence everywhere and at the same time, is an omnipotent vision, not completely unknown to control engineers and scientists of automation, animating the lifeless. But knowing some of the organisers and participants, I hope this conference of the IFAC, to be in the tradition of N. Wiener's concern in "Cybernetics: or Control and Communication in the Animal and the Machine" (p. 28), writing about the first industrial revolution as the devaluation of the human arm and the second industrial revolution as the devaluation of the brain: "However, taking the second revolution as accomplished, the average human being of mediocre attainments or less has nothing to sell that is worth anyone's money to buy. The answer, of course, is to have a society based on human values other than buying or selling." Therefore beyond the title of this conference "Cost oriented Automation" I am also looking for aspects of human-centred-ness in ubiquitous computing.

Some motivations of Mark Weiser, when he introduced UbiComp, obviously were influenced by the anthropological studies of work life of Lucy Suchman (1985) and Jean Lave (1991) who "teach us that people primarily work in a world of shared situations and unexamined technological skills. However the computer today is isolated and isolating from the overall situation, and fails to get out of the way of work." (Weiser, 1993). Ideas of the "intimate computer" (Kay 1991), "rather like a human assistant" (Tesler 1991) or "Rechner im Rücken" (Bruns 1993) were all around and found some condensed presentation in a Communication of the ACM Volume "Back to the real World". There were mainly three approaches to face this re-discovery of the real reality connected to the virtual reality from a sensory and control theoretical point of view:

- sensors and actuators being integrated into real objects, recognising the intention of the user and the environment (reaction model),
- sensors and actuators being at the fingertips of the user, manipulating the real world by grasping and signing, recognised by the computer (action model),
- independent third perspective of sensing and manipulating the world.

Embedding computation in physical artefacts and spreading them throughout our environment was the first approach. A behaviour construction kit (Resnick, 1993) allowed to build models out of computerized LEGO pieces with electronic sensors which could be programmed using LEGO/Logo, able to interact with users or physical objects on a low cost level. This sensorisation of physical objects required the implementation of a model of how to react on changes, these bricks experience from the user. A different approach was to use the hands of a user, equipped with sensors, and implement a model about how to change the computational representation of the environment. Roughly speaking, in the first approach, the computer has information about tracked physical objects and a model of the user to relate changes of the physical world to actions and intentions of the user. In the second approach the computer has information about the tracked hands and body of a user and a world model to relate them to changes of its internal world representation. Two reasons for us to follow the second approach were *costs* and *controllability*. In certain application areas like modelling a production plant or a control circuit it is less expensive to sense the modellers hand than to sense all objects (figure 2-3). Furthermore, a user wearing sensors has control over them, she can turn them on or off, as opposed to a sensory world, in which she has no influence about being tracked. Of course, the most powerful method but also most expensive way is to combine these approaches and there the latter problem is in again.

Fig. 1. Theatre of the Machines: A struggle between Man, Machines and Nature. Performance at the Stuttgart Youth Theatre Festival 2000.
(Robot-Man Controlling Virtual Reality and a Marionette or Vice Versa?)

Whereas these early days of *Ubicomp* were concentrated on a more receptive view of the world, looking for new input-output-devices and how to handle **information**, later years more and more brought up the idea of an activated world with small invisible devices, sensing **and acting** into the world around us. Therefore we may see ubicomp in a narrow way as ubiquitous computing for information services (the sensory coffee-cub or refrigerator to inform about the state of real objects) or in a more broader sense as ubiquitous sensing and acting, as pervading automation. Or, as Mitchell (2003) proposes, the "trial separation" of bits and atoms is over. With increasing frequency, events in physical space reflect events in cyberspace, and vice versa. This latter view is the challenge for control people. Beside science fiction authors speculating about material compiler and mater transmitter, like Neal Stephenson (1995) with his Young Lady's illustrated Primer, a serious computer-graphics pioneer, E. Sutherland, early mentioned a vision of the ultimate display, a device able to project computer internal information into the real world like a bullet, hitting careless people. “The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such display could literally be the Wonderland into which Alice walked.” (Sutherland 1965, p. 508). However, even this far reaching view is still a display-view, a bullet is shot and then let alone. From a control perspective, closed loops are aimed at.

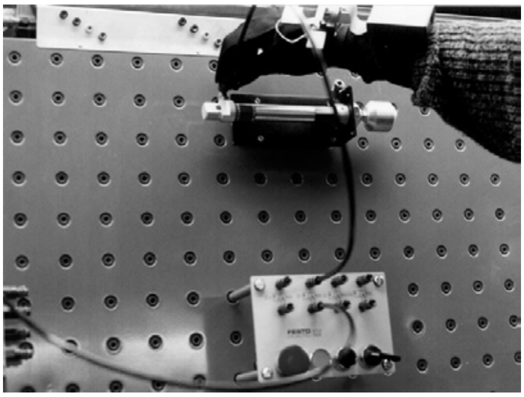

Fig. 2. Concrete Modelling of a Control System with Sensory Hand

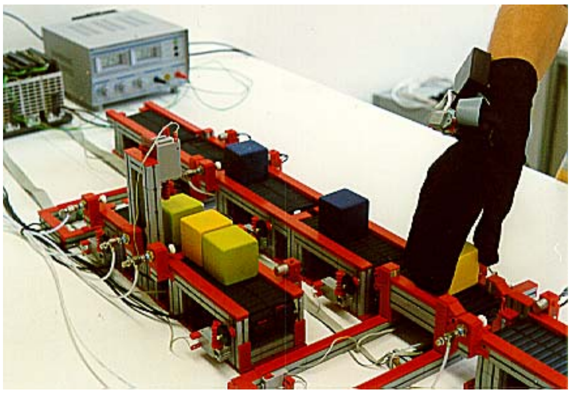

Fig. 3. Specifying dynamic systems by concrete demonstration with sensory hand

Therefore, let me only shortly cover some information technology issues, as this is done at the moment on many congresses, and concentrate instead on control issues, not so often covered. For other perspectives on Ubiquitous Computing see i.e. Strassner & Schoch (2002) and Pervasive Computing conferences.

2. CHALLENGING PROBLEMS OF UBIQUITOUS COMPUTING

Considering actual ubiquitous computing research, we find that it is still dominated by the visual and sensory technology. Augmented reality, overlapping with ubiquitous computing, is mainly discussed as an augmentation of reality through computer generated image projection into reality or into video-images of reality, but not as an augmentation by actuators and actions.

The information related view, of course, opens up enough interesting applications and problems, like

- wireless media access with appropriate physics and protocols
- input-output devices with image, gesture, speech recognition and synthesis
- architectures for distributed services
- design environments for ubiquitous computing
- geometric representation, discovery/recognition
- information-technological scalability, how to manage and select devices in open networks
- movable interactions, how do they move fluidly with the user
- machine learning for pattern recognition of behaviour, optimising performance, customisation, failure prediction
- privacy, data safety and security
- GRID computing and massive parallelism

Besides general information-technological problems of distributed systems (Eckert 2004) and real-time performance (Diethers et al. 2004) especially the geometric representation problem of one unique correspondence between a distributed real and virtual world has to be solved (Brumitt et al 2000). Among these are: How to handle contradictory facts about the physical world from multiple sensors, how to combine sensors improve discover the physical relationship between entities in the world, how to select appropriate devices. New design methods for not only useful but sometimes playful and highly experience oriented environments are necessary (Pokahr et al 2002, Mueller 1998).

The control related view rises other issues.
Ubiquitous computing is represented by a variety of different shapes and sizes, from nano-technical devices, smart cards, paper like notepads, wall sized projections, mixed reality cave elements. Weiser, had the vision, that for each person in an office there would be one or two boards, tens of pads, hundreds of tabs, and one could add, thousands of nano-objects. In some sense, this is not yet true for the office, but consider everyday surroundings and the statement of Intel-Chairman A. Grove, that the average US-American encounters 70 microprocessors each day before lunch, mainly in consumer electronics at home, in elevators and security systems of public spaces and in vehicles and traffic control systems! I could not count them this morning, because they aught to be invisible, but a rough estimation brought me to …. However, the increasing pervasion or **ubiquitous computing and acting**, opens up old and new frontiers: technological and social (pedagogical,

psychological, ethical). Here, I will cover mainly technological issues.
Maurer (2004) foresees the PC in 10 years as being one almost on a credit card with no hard-disk, keyboard and screen, but instead distributed over users body with projection glasses, tiny cameras, voice transmitting collar, head-tracking and body localisation devices, full global network integration. Again, this vision is mainly an information view, missing an action support. Exoskeleton devices and helpful physical ghosts could be around. The ultimate penetration of the physical and the information world would not be if all objects have a RFID Chip, as sometimes stated, but if they also have some means of remote action support.

M. Weiser had this far reaching perspective, he distinguished ubiquitous computing from PDAs and autonomous software agents using as example the lifting of a heavy object. "You call in your strong assistant to lift it for you, or you can be yourself made effortlessly, unconsciously stronger and just lift it … ubiquitous computing aims at the latter" (Weiser, 1993). This could be understood metaphorically, but I would like to interpret it in a concrete way. Then we face the problem of how to handle effort and flow of energy in a distributed human-machine related way. CoBots in an assembly line, production factory, the household or an intelligent building, as elucidated by Erbe (2004), represent good examples of ubiquitous automation. This close coupling of physical objects and information is a domain, control people are very familiar with. Therefore, ubiquitous automation might be an important field of future work of IFAC.

Weiser's example leads me to a related research field with similar, sometimes inverse problems: *Humanoids*, *Telepresence* and *Intelligent Buildings* research (Hamel 2003, Becher et al 2003, Hirche et al 2003, Hirche & Buss 2003, Morpha 2003, QRIO 2003, Streitz et al 1999).
How can autonomous robots recognise and act in a changing natural environment and how can they collaborate with surrounding humans and other CoBots? Humanoids share their workspace with humans. They could take over the heavy load of a task, letting the human fine adjust and control the work (Takubo et al 2000). Distributing this functionality into visible and invisible surrounding objects yields to ubiquitous computing and acting. To experience problems and possibilities on a low cost experimental level, with off-the shell toys and tools, we need some well developed similarity theory, as it is known from engineering disciplines, like fluid dynamics scaling in relation to Reynolds Number (length of object * velocity of flow / cinematic viscosity of the medium). There is a strong theoretical background in control theory, but no clear criteria and evaluation scheme to compare different control schemes. Melchiori (2003) contributed to close this gap, and presented an overview and criteria for the analysis and comparison of control schemes for tele-manipulation systems. He also found that there is a need for laws of proper scaling even for force/velocity systems in higher dimensions. But ubiquitous computing and acting requires more than a representation and application of just forces. All physical phenomena could be candidates for mediation. This means, the relating laws of control, criteria of stability, inertia and damping, tracking, stiffness, applied to forces and velocities of robot arms should be generalised to effort/flow phenomena in the sense of Bond-Graph theory to cover full ubiquitous computing. This is one important theoretical challenge I see. *Bond-Graph Theory* still has a missing link to computer science. Graph-transformations, as they are used in language processing (compiler building, theorem proof etc) offer powerful means to handle graph representations, graph grammars and replacement algorithms. As there is a strong theoretical and experimental background in more or less disjoint disciplines, like electrical, thermodynamic, mechanical and fluid-dynamic engineering, the existing unified concepts, like Petri-Nets and Bond-Graphs, could improve the transfer and merge of practical system solutions for ubiquitous computing and acting. Unified views of information and energy flow, the merging of discrete and continuous system behaviour, self-similarity and hierarchical composition of large distributed systems are still posing non-trivial problems.

For cost oriented ubiquitous computing and acting, we need good simulation and reality integration. Wollherr & Buss (2004) demonstrate how a MAT-LAB Realtime Workshop in connection with Simulink on a Realtime (RT) Linux can be used to combine virtual reality with realtime reality control of a SCARA robot balancing an inverted pendulum and a car prevented to roll over using impedance control. This combination of real and virtual representations proved not only to be useful for the human-system interaction, but also for students and their under-standing of the adequate or inadequate reduction of simulation models (i.e. not modelled system pro-perties such as friction). In our mixed reality learning environment (see below) we found similar benefits, however we also missed the inadequate possibilities of powerful modern simulators to allow modelling and simulation on the fly. Justified by a tradition of well designed simulation modelling separated from experimentation: first build a model, then compile it to run efficiently and then perform series of repro-ducible experiments, then draw consequences for reality or the model, this procedure is still dominating the simulation community but inadequate for inter-active worlds. When we faced the problem to work with pneumatic cylinders, valves, pressure sources and connecting tubes to build electro-pneumatic systems interactively in virtuality and wanted to experience a similar behaviour as in reality already during the building process, there was a problem. Simulators do not support this modelling with components "already under physics", on the fly. To connect a tube under pressure to a cylinder should immediately drive out the piston and a tube with one open end should whip around.

Learning system behaviour by demonstration is a further challenge to be faced, if ubiquitous “intelli-gent” devices want to adapt itself to a changing environment and the habits of users. In recent projects supported by the DFG (German Science Foundation) we investigated possibilities to generate abstract behaviour descriptions for robot tasks and plc-algo-rithms from concrete movements of sensory hands (Fig. 3) (Schäfer & Bruns 2001). We were able to generate simple plc-programs this way, but much more research has to be done, to be able to handle open situations in ubiquitous computing and acting. According to Moore’s Law, the cost of a system on a chip including input and output controller is falling to a few cents. One important question is, how to integrate the expectable manifold of devices into a controllable system. Some research counts on self-organizational principles to handle these “Spray Computers” (Mamei & Zambonelli, 2003), clouds of microcomputers to be sprayed into the environment With specific smart sensing and effecting functio-nality they imagine to go to a local store and buy a “pipe repairing” spray of a cloud of microcomputers. In a recently started joint initiative between industry and German Universities a similar focus is on *Organic-Computing*: learning from nature to adapt and emulate self-organizational principles and architectures to handle complexity. Envisioned applications of these controller/observer driven systems are cars, intelligent buildings, intelligent autonomous robots and vehicles and production systems (OC, 2004).

User-Interface design will completely change. Driven by classical ergonomics, software ergonomics first was concentrated on physiological and psychological “objective” performance criteria of man-(soft)-machine or task relations. Scandinavian approaches towards cooperative design (Ehn, 1988), Useware design (Zühlke & Wahl 1999), interaction design (Caroll 1991, Cooper 1999) and experience design (Laurel 1986, Hagita 2003, Paulos 2003) more and more shift towards a playful emotional useless and useful relation to an everyday environment. This means, that new aesthetic forms will emerge and have to be supported in the design process. Fishwick (2002) and others investigate means to express functionality and behaviour in alternative aesthetic styles with a broad variety of user oriented materials, symbols and rules. To support translations between these notations is an emerging research area.

To sum up, we need

- Frameworks of Control Models (Melchiorri, 2003)
- Unified models of mapping physics to information and vice versa (Bondgraphs, Paynter, 1996 and Petri-Nets)
- Physical scalability
- Advanced sensor-actuator interfaces (Hyper-Bonds, s.b.)
- Mixed reality frameworks of distributed model-view-control
- Mixed reality multi user environments (who owns the real process?)
- Tactile interfaces (tele-manipulation)
- Abstractions from recorded activities and events, specifying by demonstration
- Low power devices and integrating and alternating mechatronic perspectives on form, function and behaviour
- More consideration of the importance of enjoyment, bridging perspectives of toys and tools

Two concepts, recently developed in my group, may be a modest contribution to ubiquitous computing: *complex objects* and *hyper-bonds*. Complex objects are objects having one real part and several virtual representations closely coupled.

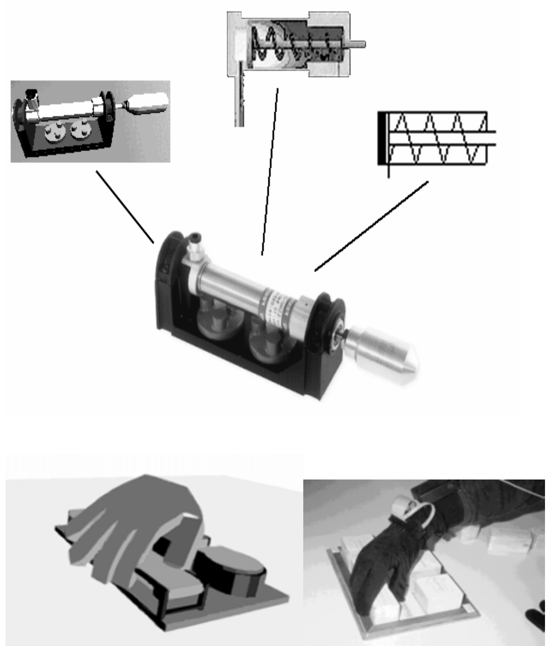

Fig. 4: Complex Objects with real tangible parts and various digital representations

In Fig. 4, two different kinds of complex objects are presented, one for a pneumatic cylinder and one for a conveyor belt. Computer based links between real and virtual parts ensure the synchronization of their states. They can be realized by video-image-recognition or, as shown in figure 3, by data glove tracking. Starting from a reference situation, changes of state are sensed by a graspable user interface and used to update the complementary part (Bruns, 1993). The term *complex object* is an allusion to the mathematical notion of complex numbers. Similar to complex numbers, having a real and an imaginary part, the complex object contains an abstract, virtual object with enriched possibility of mathematical treatment and behavior (algorithms, data-structures) and the controlled automation device as its projection into reality. With construction kits, containing sets of these complex objects for specific application areas, it is possible to construct a system in reality and synchronously generate a corresponding virtual model, which can be tested, analyzed and transmitted to remote places.

The concept of Hyper-Bonds is an electromechanical interface mechanism to sense and generate physical effort and flow phenomena and to relate this to the well known theory of bond-graphs. A first implementation of this concept has been demonstrated in a European project DERIVE – Distributed real and virtual Learning Environment for Mechatronics and Tele-Service (Fig. 5). However, the implementation is for non-time-critical electro-pneumatic systems of state-automata type, with discrete pressure and voltage. This allows a distribution via low band-width Internet. To integrate and distribute hard real-time analogue processes, like remote force-feedback, is still heavily restricted by the quality of the Internet, by process control sensors and actuators and by theoretical issues of merging and cutting bond-graphs and Petri-net simulations.

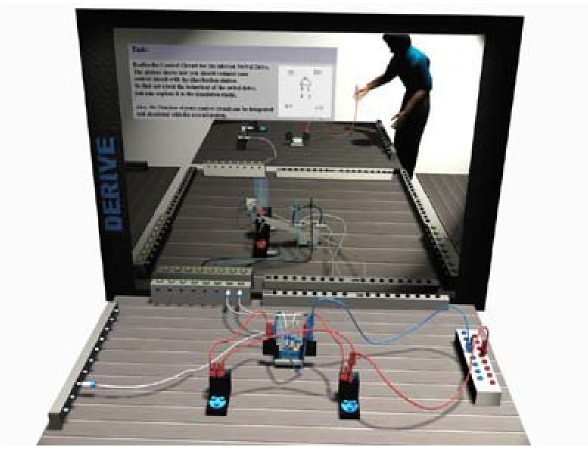

Fig. 5. Distributed real and virtual world, mixing physical and information phenomena

In two running projects Lab@Future and MARVEL we are developing perspectives and prototypes about future laboratory work. Many of the above questions have to be considered there. In these projects we extended Milgram & Colquhoun's (1999) Mixed Reality Taxonomy by emphasizing the focus of attention and real experiences, Fig. 6-7. Three dimensions are

- focus of attention between reality and virtuality
- centeredness as location of our experience with sensing and acting
- directness of the action-reaction control circuit

Centeredness is egocentric, if we see, hear, feel, as if we were in the center. Exocentric is a perspective if we consider the world from a distant third-person perspective. Directness of control would be in the sense of our known control models, together with cognitive directness (orientation, time-delay, multi-sensory reception). This taxonomy could help to systemize the design and evaluation of mixed reality applications.

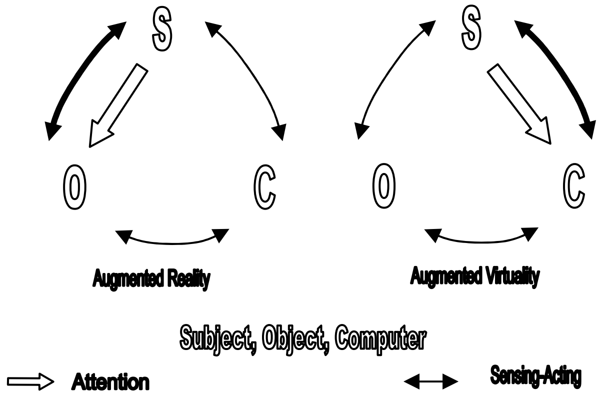

Fig. 6: Relations in Mixed Reality

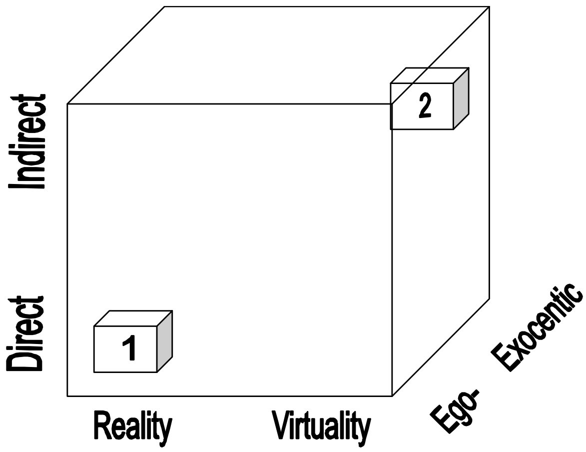

Fig. 7: Taxonomy of Mixed Reality (Control, Location, Perspective)

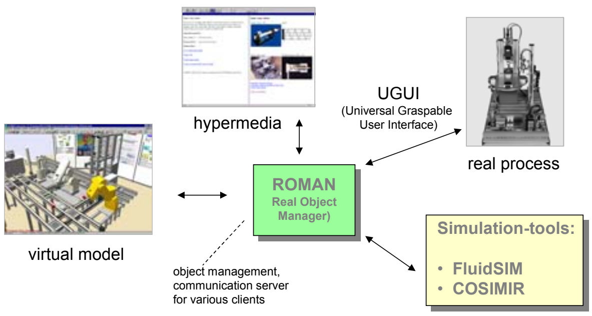

Fig. 8. System Architecture Overview

In DERIVE we faced a low scale distributed problem with a central server-client architecture. The architecture consists of several modules that together build the system.

This will certainly be inadequate for massively parallel systems. The challenge will be to combine many of these types of server, recording and handling the states of and accesses for overlapping realities.

3. SOCIAL ASPECTS

Tracking the life-cycle of perishable food, workflow-systems, personal access control, identification of objects and persons in public and work places might be a promising perspective, but the arising problems are immense. The right of informational self-determination will be strongly attacked by these developments. In a recent case in Germany it was discovered that a food-store distributed active smart-cards among their customers being able to collect data about their custom preferences and use behaviour. Ubiquitous Computing rises in a new way the question of transparency. One up-to-date aim of computer-design is transparency, making the system invisible, independent of size, location, physical implementation: computing power everywhere at every time. If we do not see the all surrounding system, the possibility of misuse increases, be in the name of home security or public safety.
I have no solutions for these problems, but the more we reflect about them and the more sensibility we develop for these questions, the higher the chance, that we are not overrun by technology.

Wenn der Schein wild wird nach Gestalt, wird er den Spiegel zum Bersten bringen

Botho Strauß
When display is getting wild for form, it will bring the mirror to burst
(translation WB)

I am not as pessimistic as the dramatist, who fears, that we are entering an era of collective trance, but I believe that we have a lot to do, to be aware of the possibilities and dangers of a world where computing is everywhere.

In another student project we animated a rose-garden through a nightly installation *Sensory Garden*, where visitors could experience the virtual duplication of a lifeless stone statue, flowers and humans in a mixed reality presence (Fig. 9). These performances are some modest low cost tries to face the above questions (Richard 2004).

Fig. 9: Statue Aegina and her double on a projection wall

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