From Ancient Machines to Intelligent Robots - A Technical Evolution -

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Abstract – Since pre-historic times mankind has dreamt of machines that imitate organisms or even surpass humans in their abilities, and time and again ingenious craftsmen B *and later engineers* B *have attempted to actually build such machines. Today=s robots are the latest result of an ongoing technical evolution that has progressed over more than 2000 years.*

Many robots work in factories where they produce goods in huge quantities and excellent quality at low costs, but recently we can observe the emergence of new classes of robots. These novel A*service robots*@ *are not designed to produce goods, but to provide useful services at workplaces or in homes, or simply to entertain and comfort humans.*

Some fundamental characteristics of past, present and future robots are reviewed. In particular, the humanoid robot HERMES, an experimental robotic assistant of anthropomorphic size and shape, and the key technologies developed for it, are introduced. HERMES provides services, such as transportation and manipulation of objects, and assists humans, e.g., by giving information. It can see, hear, speak, and feel. In a long-term test (6 months) at a museum it chatted with visitors in natural language in German, English and French, answered questions and performed services as requested by them.

Keywords *– history of robotics, industrial robots, service robots, personal robots, HERMES.*

I. INTRODUCTION

Machines that resemble humans or animals have fascinated mankind for thousands of years, but only in the 16th century technology and craftsmanship became sufficiently advanced both in Europe and in Japan to allow the construction of automated dolls (Figure 1). What we call robots today are machines that incorporate at least some computational intelligence, and such machines have existed only for a few decades.

There is no precise definition, but by general agreement a robot is a programmable machine that imitates the actions or appearance of an intelligent creature, usually a human. To qualify as a robot, a machine has to be able to do two things: one, get information from its surroundings, and two, do something physical, such as move or manipulate objects. Robots can be huge and massive 50 meters long machines or little tiny manipulators in micro- or nanometer space. They can be intelligent and act autonomously (unpredictably) on their environment, or dumb machines repeatedly making the same predictable and precise motions without a pause, or something in-between. They are propelled by wheels or tracks, move snake-like or have legs; they work in laboratories, offices or museums, act in outer space or swim in the deep sea. Robots are made to accomplish dirty, dull and dangerous work, and more recently, to entertain and to be played with. They construct, assemble, cut, glue, solder, weld, paint, inspect, measure, dig, demine, harvest, clean, mow, play soccer and act in movies. This Amulti-cultural society@ has grown in recent years to more than one million Amembers@.

The most wide-spread robots today are industrial robots. They work in factories where they produce goods in huge quantities and excellent quality at low costs (Figure 2). They are useful and they are the basis of much of the prosperity that we enjoy in the industrialized parts of the world, but they are not very intelligent.

As a consequence of the recent advances in information technology we can observe the emergence of new classes of robots. These novel Aservice robots@ are not designed to produce goods, but to provide useful services at workplaces or in homes, or to simply entertain and comfort humans.

In the future we may see Apersonal robots@ that exist in ordinary peoples= homes or work places and combine the traits of friendly companions, competent assistants and useful servants. Such robots will require levels of intelligence, robustness, adaptability and dependability that in their combination exceed greatly what is attainable with existing technology. While presently robotic servants or butlers exist only in the form of early

Fig. 1. Karakuri doll serving tea to a guest (Japan, 1800).

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Fig. 2. Modern industrial robots performing typical manufacturing tasks: spot welding, material handling and assembly [KUKA 2009].

prototypes in a few research laboratories, they are expected to become in the future as ubiquitous as PCs are today.

The remainder of this paper consists of two parts. In the first part some fundamental characteristics of past, present and future robots are reviewed (section 2). In the second part (sections 3-6) the humanoid robot *HERMES*, an experimental robotic assistant of anthropomorphic size and shape, and the key technologies developed for it, are introduced (Figure 8). *HERMES* can see, hear, speak, and feel, as well as move about, localize itself, build maps of its environment and manipulate various objects. It learns continuously through observations and dialogues, and interacts dependably with people and their common living environment. It provides services, such as transportation and manipulation of objects, and assists humans, e.g., by giving information. In its dialogues and other interactions with humans it appears intelligent, cooperative and friendly. In a long-term test (6 months) at a museum it chatted with visitors in natural language in German, English and French, answered questions and performed various services as requested by them.

II. THE EVOLUTION OF ROBOTS

A. Ancient Robots

Since pre-historic times mankind has dreamt of machines that imitate organisms or even surpass humans in their abilities, and time and again ingenious craftsmen B and later engineers B have attempted to actually build such machines. Probably the oldest mentioning of autonomous mobile robots may be found in Homer=s Iliad (written circa 800 B.C.). According to this source, Hephaistos, the Greek god of smiths, fire and metal-working, built 20 three-legged creatures (tripods) Awith golden wheels beneath the base of each that of them-selves they might enter the gathering of the gods at his wish and again return to his house@ (book 18, verse 375). They are described as being powerful and intelligent, with ears and voices, willing to help and work for him [Homer 800 B.C.]. B Details regarding their technology are left to the imagination of the reader.

Mechanical animals that could be animated by water, air and steam pressure were constructed by Hero of Alex-andria in the first century B.C. [Woodcroft 1851].

Much later, depending on dexterous manufacturing knowledge for clockworks starting in the 16th century, skilled craftsmen in Western Europe succeeded to design anthropomorphic devices that could imitate a human=s movements or behaviors in general. Mechanical dolls performed simple life-like acts, such as drawing, writing short phrases or playing music [Heyl 1964].

Japanese craftsmen of the 18th century created many

Fig. 3. Modern computer-controlled *karakuri* "Ciélo arpéggío" with four dolls. The doll on the right plays an instrument as the other ones dance to the tune [Mudo 2003].

varieties of automated mechanical *karakuri* dolls that could perform such acts as drawing an arrow from a quiver, shoot it from a bow, and display pride over the good shot. Another famous *karakuri* doll (Figure 1) could bring a tea cup to a guest over distances of about 2 m (size of a *tatami* mat). When the guest removed the cup from the tray, the doll ceased to move forward, turned around and returned to its starting place [Nipponia 2000]. What makes those *karakuri* particularly fascinating is that their mechanisms are usually constructed entirely from wood.

Modern *karakuri* combine a beautiful and artistic appearance with sophisticated computer-controlled mechanics inside. Figure 3 shows as an example a *karakuri* created by the artist Yuriko Mudo and on display in a department store in Nagoya station. Such dolls may nowadays be seen in many public places, hotel lobbies and restaurants in Japan.

Fig. 4. Industrial robots with award-winning design: KUKA PA 180 (red dot award "best of the best 2002"), KR 1000 titan, KR 16 (red dot awards "product design 2008").

B. Industrial Robots

Other successors to the ancient robots are today=s industrial robots. While they may be more useful, they are certainly less artistic, although manufacturers exist who strive for a design that is not only functional, but also esthetically appealing. For instance, the German manufacturer KUKA Robotics has won several design awards for its industrial robots, among others the internationally most renowned Ared dot design award@ (Figure 4).

Industrial robots are of great economic and technological importance. Until the end of 2007 approximately 1.25 million robots had been installed worldwide since their introduction in 1961 [IFR 2008]. At that time a minimum of 995,000 were still in operation, for the most part (65-80%) in automobile and metal-manufacturing. Experts estimate that by the year 2011 about 1.2 million industrial robots will be employed world-wide. This number results from the very conservative estimation that the average length of a robot's service life is 12 years while a pilot study indicated that the actual service life is closer to 15 years. Typical applications include welding car bodies, spraying paint or glue on appliances, assembling printed circuit boards, loading and unloading machines, and placing cartons on a pallet. Where industrial robots are being used their employment has almost displaced degrading work conditions that used to be commonplace in mass production from the beginning of the industrial revolution.

People's fear of being replaced by robots, ubiquitous in the media 15-20 years ago, has almost vanished. It is acknowledged that those industries that have employed industrial robots (e.g., the automobile industry) flourish and employ more people, while industries that renounced robots (e.g., consumer electronics) have largely migrated to low-wage countries. It is no secret that sooner or later people will retreat from production processes in factories and seek new, more diversified kinds of labor. Any industrial nation should be prepared for this structural change that is only gradually taking place as it has, as a matter of fact, at all times [Christaller et al. 2001].

Although present industrial robots contribute very much to the prosperity of the industrialized countries they are quite different from the robots that researchers have in mind when they talk about Aintelligent robots@. Today=s industrial robots are not creative or innovative, do not think independently, do not make complicated decisions, do not learn from mistakes, and do not adapt quickly to changes in their surroundings. They rely on detailed teaching and programming in terms of positions and orientations of their end effectors (Figure 5). For cost and reliability reasons they mostly deny using sensors, at the cost of needing a carefully prepared environment. Because of their Ablindness@ and Anumbness@ it is difficult to adapt their programming to slightly changed environmental conditions or modified tasks. Nevertheless, they guarantee high precision (repeatability better than 0.1 mm) for seemingly endlessly repeated movements with high and varying loads (up to 1000 kg) [KUKA 2008]. However, their strength, positioning accuracy and stiffness come along with a high mass-to-payload ratio of 10:1 or more. Although carbon fiber materials are partly being used [KUKA 2001], the mass-to-payload ratio is still one order of magnitude worse than that of the human arm. The kinetic energy of this kind of robots is potentially so high, and their intelligence so limited, that space-sharing human-robot interaction B as largely required by (personal) robotic assistants B is only possible with dedicated safety equipment.

C. Field and Service Robots

Although the vast majority of industrial robots today are used for manufacturing goods in factories, advances in technology are also enabling robots to automate many tasks in non-manufacturing industries such as agriculture, construction, health care, retailing and others. These so-called Afield and service robots@ aim at the fast growing service sector and promise to be a key product for the next decades.

According to the International Federation of Robotics (IFR), a service robot is Aa robot which operates semi- or fully autonomously to perform services useful to the well-being of humans and equipment, excluding manufacturing operations@ [IFR 2008]. This still preliminary definition is based on a definition introduced in 1994 by the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Stuttgart, in a study about service robots for innovative servicing technologies [Schraft et al. 1994]: AA service robot is a freely programmable moving machine that partially or fully autonomously delivers services. Services are activities being performed not to manufacture goods, but to provide services for humans and equipment@ (translated into English from a German source). Both definitions should not be considered as fixed, but rather as working definitions.

The before-mentioned 1994 IPA study pioneered in analyzing and classifying possible service industries in which the employment of dedicated robots could be useful. They are grouped into eight branches: health care; rehabilitation; construction; community support, environmental protection and agriculture; retail, transportation and traffic; hotels and gastronomy; security, radiation and civil protection; household, hobby, leisure time. In another study [Schraft & Schmierer 2000] show different service scenarios based on products, prototypes, demonstrators and concept studies, both from industry and academia. The web page of the IEEE-RAS Technical Committee on Service Robots (www.service-robots.org) keeps an up-to-date list of these service robots.

In the 1960s and 1970s some ambitious researchers at Stanford University, Jet Propulsion Laboratory and Carnegie Mellon University created a novel kind of robots: computer-controlled vehicles that ran autonomously in

Fig. 6. Autonomous road vehicle able to follow a road at a record speed of 96 km/h in 1987.

their laboratories and even outside with a video camera as the main sensor [Nilsson 1969], [Moravec 1980]. Due to the limited computing power and insufficient vision technology of the time, the speed of those early vehicles

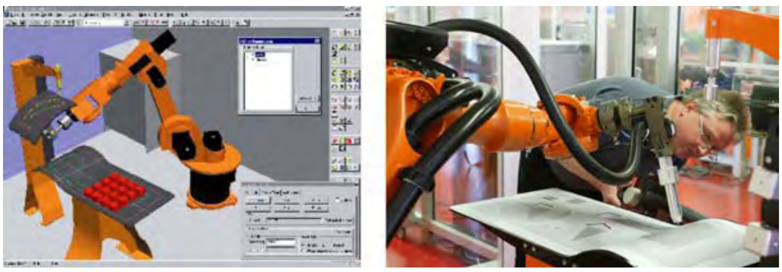

Fig. 5. Two industrial robot programming paradigms. Left: error-prone offline programming. Right: time-consuming online teach-in of points.

was only about 1 m in 10-15 min, and the environment

Fig. 7. Typical service robots: mobile transportation robot Helpmate [King, Weiman 1990], vacuum cleaning robot Roomba [iRobot 2002], airplane cleaning robot Skywash [Schraft & Schmierer 2000].

had to be carefully prepared to facilitate image interpretation.

In 1987 technology had advanced to the point that an autonomous road vehicle (Figure 6) could follow a road at a speed of 96 km/h, a world record at that time [Dickmanns, Graefe 1988]. In 1992 the objects that are relevant for road traffic situations could be recognized in real time from within a moving vehicle [Graefe 1992], making it possible for an autonomous driverless vehicle to mix with ordinary vehicles in ordinary freeway traffic. Although most major automobile companies now operate autonomous cars in their research laboratories, only a few sub-components are sold to the consumer today as add-ons for supervising and assisting manual driving. Autonomous vehicles operate today only within closed areas such as theme parks or railways. Only when liability and other legal and societal issues are solved, they could be sold to the public.

Examples of field and service robots that are actually in use are autonomous cleaning robots for floors [Endres et al. 1997], [Electrolux 2001], [iRobot 2002], facades [Miller 2000], windows [IPA 2002] and airplanes [Schraft & Schmierer 2000]; construction robots for high-rise buildings [Balaguer & Abderrahim 2008], tunnels [Honegger et al. 1997] and roads [Pimentão 1996]; crop harvesting [Ollis & Stentz 1997] and lawn-mowing robots [Friendly Robotics 2003]; surgical assist robots [Pransky 1997]; and security guards [Cybermotion 2003], [Robowatch 2007] and mail delivery robots [Tschichold 2001]. Figure 7 shows a few examples.

Field robots have also helped scientists explore strange new worlds and environments that are hazardous or unsuitable for humans. Remotely controlled rovers have explored volcanos [Wettergreen 1995], deserts and Antarctica [Wagner et al. 2001], or Mars [Matthies 1995];

deep sea diving robots have inspected the Mid-Atlantic Ridge at depths of up to 6000 meters and will soon explore the deepest known part of the oceans, 11 km below the surface [Bowen et al. 2008].

Like the manufacturing industries the service industries increasingly depend on intelligent aids for better working conditions, improved quality and lower cost. Due to the diverse nature of service areas, field and service robots come along in many species and cover a huge variety of tasks and environments B unlike their classical industrial counterparts whose working environments and task ranges are fairly restricted. However, most field and service robots are special-purpose machines with dedicated mobility bases and manipulation (or process) devices.

They have been employed in environments where they may, or even have to, come into contact with the public, and some of them actually interact with people. They can, to a very limited extent, perceive their environment and they display traces of intelligence, e.g., in navigation and obstacle avoidance. Combined with their slow speed of motion this allows some of them to operate safely in the vicinity of ordinary humans. Most of these service robots have the following characteristics in common:

- Each one of them is a specialist, able to deliver only one kind of service in only one kind of environment.
- Their sensory and cognitive abilities and their dependability are barely sufficient for accomplishing their given task most of the time.
- They are of a more or less experimental nature and have not yet proven their cost effectiveness.

Much R&D effort is being spent to overcome these deficiencies and it is hoped that service robots will eventually be economically as important as industrial robots are today.

D. Personal Robots

A novel kind of robots is currently evolving. While industrial robots produce goods in factories, and service robots support, or substitute, humans in their work places, those novel Apersonal robots@ are intended to serve, or accompany, people in their private lives and share their homes with them. Two types of personal robots have so far emerged: One type comprises robots that are intended to make people feel happy, comfortable or less lonely or, more generally speaking, to affect them emotionally; these robots usually cannot, and need not, do anything that is useful in a practical sense. They may be considered artificial pets or B in the future B even companions. Therefore, they are also called personal robotic pets or companions. The most famous one is AIBO, sold in large numbers by Sony from 1999-2006. Weighing about 2 kg it resembles in its appearance and some of its behaviors a miniature dog. The other type of personal robot is intended to do useful work in and around peoples= homes and eventually evolve into something like artificial maids or butlers. Such robots may be called personal robotic servants or assistants.

In many developed societies the fraction of elderly persons is growing and this trend will continue for at least several decades. Consequently, it will be more and more difficult to find enough younger people to provide needed services to the elderly ones, to help them with their households, to nurse them and even to just give them company. We may hope that personal robots will help to alleviate these problems. Looking at it from a different point of view, and also considering the fact, that many of those elderly people are fairly wealthy and have relatively few heirs for whom they might want to save their wealth, personal robots promise to create large and profitable markets for technology-oriented companies. It is not surprising that major companies, such as Fujitsu, NEC, Omron, Sanyo, Sony and Honda are developing and marketing personal robots [Fujitsu 2003], [NEC 2009], [Omron 2001], [Sanyo 2002], [Fujita, Kitano 1998], [Sakagami et al. 2002].

Technologically, pet robots are much less demanding than servant robots. Among the reasons are that no hard specification exists for what a pet robot must be able to do, and that many deficiencies that a cute pet robot might have may make it even more lovable in the eyes of its owner. Assisting a pet robot in overcoming its deficiencies may actually be an emotionally satisfying activity. A servant robot, on the other hand, simply has to function perfectly all the time. Even worse: While a maid will be forgiven her occasional mistakes if she offers sincere apologies, no technology is available for implanting the necessary capacities for sincerity, feeling of guilt and compassion in a robot. In fact, marketable servant robots are far beyond our present technology in many respects and all personal robots that have been marketed are pet robots.

Pet robots have already demonstrated their indirect usefulness in systematic studies. For instance, Shibata and coworkers [Wada et al. 2003] have carried out rehabilitation experiments in various hospitals with a white furry robot seal called Paro (the name stems from the Japanese pronunciation of the first letters of "personal robot"). Paro has 7 degrees of freedom, tactile sensors on the whiskers and most of its body, posture and light sensors, and two microphones. It generates behaviors based on stimulation (frequency, type, etc.), the time of day and internal moods. Paro has one significant advantage over artificial cats and dogs: people usually do not have pre-conceived notions about seal behavior and are unfamiliar with their appearance, and thus people easily report that the interaction with Paro seems completely natural and appropriate. The seal's therapeutic effect has been observed in hospitals and among elderly persons. During several interaction trials in hospitals carried out over several months, researchers found a marked drop in stress levels among the patients and nurses. Nurses of an elderly day care center reported that the robot both motivated elderly people and promoted social communication.

Servant robots, on the other hand, exist only in the form of early prototypes in a few research laboratories, and then often not even as complete robots. In some

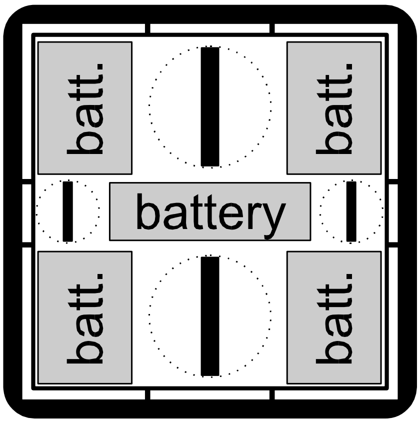

Fig. 9. *HERMES'* omnidirectional undercarriage with active (large) and passive (small) wheels, bumpers and batteries

cases only a head, or the image of a simulated head on a screen, exists, in other cases only a torso with a head and arms, but without the ability of locomotion.

III. THE HUMANOID ROBOT *HERMES*

A. Overview

We have developed the humanoid experimental robot *HERMES* (Figure 8) to advance the technology of servant robots. What makes it special is the great variety of its abilities and skills, and the fact that its remarkable dependability has actually been demonstrated in a long-term test in a museum where it interacted with visitors several hours a day for six months.

With its omnidirectional undercarriage, body, head, eyes and two arms *HERMES* has 22 degrees of freedom and resembles a human in height and shape. Its main exteroceptive sensor modality is monochrome vision, but it also has auditory and haptic senses.

In designing it we placed great emphasis on modularity and extensibility of both hardware and software [Bischoff 1997]. It is built from 25 drive modules with identical electrical and similar mechanical interfaces. Each module contains a motor, a Harmonic Drive gear, a microcontroller, power electronics, a communication interface and some sensors. The modules are connected to each other and to the main computer by a single bus. The modular approach has led to an extensible design that can easily be modified and maintained.

Both camera Aeyes@ may be actively and independently controlled in pan and tilt degrees of freedom. Proprioceptive sensors add to *HERMES*= perceptual abilities. A multimodal human-friendly communication interface built upon natural language and the basic senses B vision, touch and hearing B enables even non-experts to intuitively interact with, and control, the robot.

B. Hardware

HERMES has an omnidirectional undercarriage with 4 wheels, arranged on the centers of the sides of its base (Figure 9). The front and rear wheels are driven and actively steered, the lateral wheels are passive.

The manipulator system consists of two articulated arms with 6 degrees of freedom each on a body that can bend forward (130°) and backward (-90°) (Figure 10). The work space extends up to 120 cm in front of the robot. Each arm is equipped with a two-finger gripper that is sufficient for basic manipulation experiments.

Main sensors are two video cameras mounted on independent pan/tilt drive units ("eye modules"), in addition to the pan/tilt unit ("neck module") that controls the common "head" platform. The cameras can be moved with accelerations and velocities comparable to those of the human eye.

A hierarchical multi-processor system is used for information processing and robot control (Figure 11). The control and monitoring of the individual drive modules is performed by the sensors and controllers embedded in each module. The main computer is a network of digital signal processors (DSP, TMS 320 C40) embedded in a ruggedized, but otherwise standard industrial PC. Sensor data processing (including vision), situation recognition, behavior selection and high-level

Fig. 8. Humanoid experimental robot *HERMES*; mass: 250 kg; size: 1.85 m x 0.7 m x 0.7 m

motion control are performed by the DSPs, while the PC provides data storage, Internet connection and the human

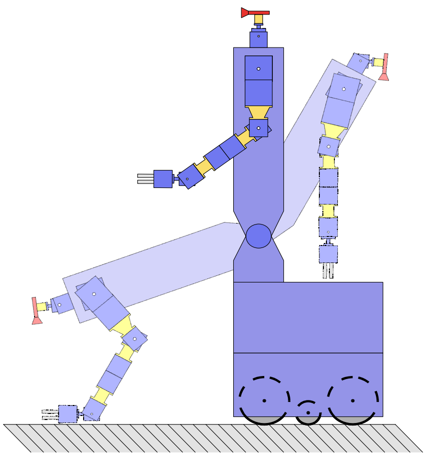

Fig. 10. A bendable body greatly enlarges the robot's work space and allows the cameras to be always in a favorable position for observing the hands.

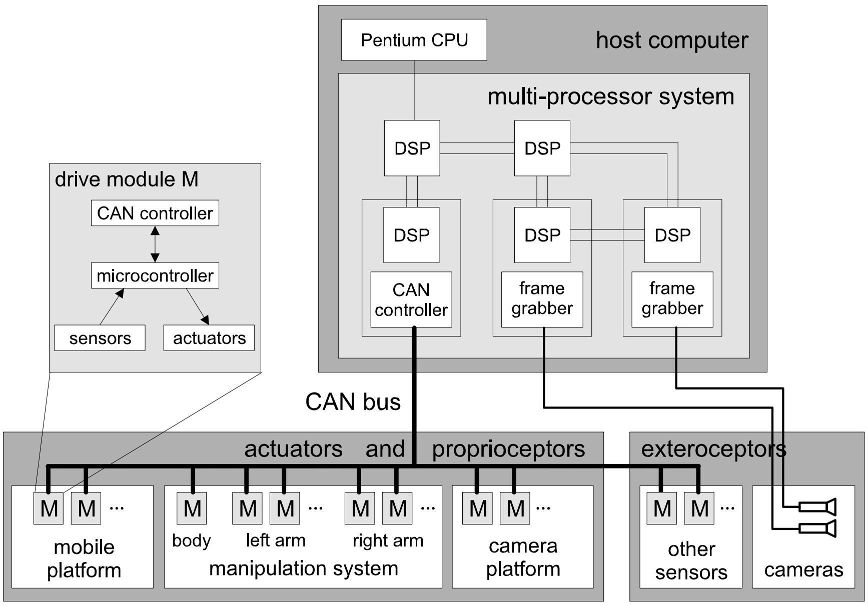

Fig. 11. Modular and adaptable hardware architecture for information processing and robot control.

interface.

A robot operating system was developed that allows sending and receiving messages via different channels among the different processors and microcontrollers. All tasks and threads run asynchronously, but can be synchronized via messages or events.

IV. *HERMES'* SYSTEM AND SOFTWARE ARCHITECTURE

A. Overview

Overall control is realized as a finite state automaton that does not allow unsafe system states. It is capable of responding to prioritized interrupts and messages. After having been powered up the robot finds itself in the state "Waiting for next mission description". A mission description is provided as a text file that may be either loaded from a disk, received via e-mail, entered via keyboard, or result from a spoken dialogue. It consists of an arbitrary number of single commands or embedded mission descriptions that let the robot perform a required task. All commands are written or spoken, respectively, in natural language and passed to a parser and an interpreter. If a command cannot be understood, is under-specified or ambiguous, the robot tries to complement missing information from its situated knowledge, or asks the user via its communicative skills to provide it.

Several of the fundamental concepts developed earlier by our laboratory were implemented in *HERMES* and contribute to its remarkable dependability and versatility, e.g., an object-oriented vision system with the ability to detect and track multiple objects in real time [Graefe 1989] and a calibration-free stereo vision system [Graefe 1995]. The sensitivities of the cameras can be individually controlled for each object or image feature. Several forms of learning let the robot adapt to changing system parameters and allow it to start working in new environments immediately [Bischoff 2000]. Moreover, speaker-independent speech recognition for several languages and robust dialogues, at times augmented by appropriate gestures, form the basis for various kinds of human-robot interaction [Bischoff & Graefe 2002].

B. System Architecture

Seamless integration of many – partly redundant – degrees of freedom, numerous behaviors and various sensor modalities in a complex robot calls for a unifying approach. We have developed a system architecture that allows integration of multiple sensor modalities and numerous actuators, as well as knowledge bases and a human-friendly communication interface. In its core the system is behavior-based, which is now generally accepted as an efficient basis for autonomous robots [Arkin 1998]. However, to be able to select behaviors intelligently and to pursue long-term goals in addition to purely reactive behaviors, we have introduced a situation-oriented deliberative component that is responsible for situation assessment and behavior selection.

Figure 12 shows the essence of the situation-oriented behavior-based robot architecture as we have implemented it. The situation module (situation assessment & behavior selection) acts as the core of the whole system and is interfaced via "skills" in a bidirectional way with all hardware components – sensors, actuators, knowledge base storage and MMI (man-machine, machine-machine interface) peripherals. The skills have direct access to the hardware components. They obtain certain information, e.g., sensor readings, generate specific outputs, e.g., arm movements or speech, or plan a route based on map knowledge, and thus they actually realize behavior primitives. Skills report to the situation module via events and messages on a cyclic or interruptive basis to enable a continuous and timely situation update and error handling.

C. Skills

Most skills involve the entire information processing system. However, at a gross level, they may be classified into five categories besides the cognitive skills:

Motor skills control simple movements of the robot's actuators. They can be arbitrarily combined to yield a basis for more complex control commands. Encapsulating the access to groups of actuators, such as undercarriage, arms, body and head, leads to a simple interface structure and allows an easy generation of pre-programmed motion patterns. Motor skills are mostly implemented at the microcontroller level within the actuator modules. High-level motor skills, such as coordinated smooth arm movements, are realized by a dedicated DSP interfaced to the microcontrollers via a CAN bus (Fig. 11).

Sensor skills encapsulate the access to one or more sensors and provide the situation module with proprioceptive or exteroceptive data. Sensor skills are implemented on those DSPs that have direct access to digitized sensor data, especially digitized images.

Sensorimotor skills combine both sensor and motor skills to yield sensor-guided robot motions, e.g., vision-guided locomotion or tactile and force-and-torque-guided robot arm motions.

Communicative skills pre-process user input and generate messages for the user according to the current situation; moreover they are in charge of language processing (input and output) and of multimodal communication combining vision, touch, hearing, gestures and speech.

Data processing skills are responsible for organizing and accessing the system's knowledge bases. They return specific information upon request and add newly gained knowledge (e.g., map attributes) to the robot's data bases, or provide means of more complex data processing, e.g., path planning.

Cognitive skills are realized by the situation module in the form of situation assessment and behavior selection, based on data and information fusion from all system components. Moreover, the situation module provides general system management and is responsible for planning appropriate behavior sequences for reaching given goals, i.e., it coordinates and initializes the in-built skills. By activating and deactivating skills, a management process within the situation module realizes the situation-dependent concatenation of elementary skills that lead to complex and elaborate robot behavior.

For a more profound theoretical discussion of our system architecture which bases upon the concepts of situation, behavior and skill see [Bischoff & Graefe 1999].

V. COMMUNICATION AND LEARNING

A. Overview

Interaction and communication with humans are fundamental for any personal robotic servant. Usually

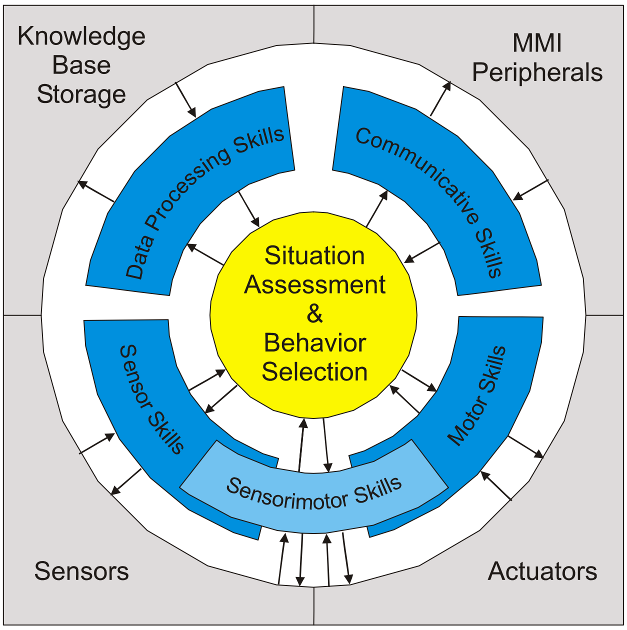

Fig. 12. *HERMES'* system architecture, based on the concepts of situation, behavior and skill.

the human partners of a servant robot will wish to use its services, but they are not necessarily knowledgeable, or even interested, in robotics. Also, they will not be motivated to modify their habits or their homes for the benefit of a robotic servant. Therefore, the robot must communicate in ways that humans find natural and intuitive, and it must be able to learn the characteristics of its users and its environment and continuously adapt itself to them. For reasons of cost no expert help will be available when these characteristics change, or when the robot is to begin to work in a new environment. Communication and learning abilities are, therefore, crucial for a servant robot.

B. Communication

Speaker-independent voice recognition. *HERMES* understands natural continuous speech independently of the speaker, and can, therefore, be commanded in principle by any non-dumb human. This is a very important feature, not only because it allows anybody to communicate with the robot without needing any training with the system, but more importantly, because anybody is able to stop the robot via voice in case of an emergency. Speaker-independence is achieved by providing grammar files and vocabulary lists that contain only those words, and provide only those command structures, that can actually be understood by the robot. In the current implementation *HERMES* understands about 60 different command structures and 350 words, most of them in each of the three available languages, English, French and German.

Robust dialogues for dependable interaction. Most parts of robot-human dialogues are situated and built around robot-environment or robot-human interactions, a fact that has been exploited to enhance the reliability and speed of the recognition process by using so-called contexts. They contain only those grammatical rules and word lists that are needed for a particular situation. However, at any stage in the dialogue a number of words and sentences not related to the current context are available to the user, too. These words are needed to "reset" or bootstrap a dialogue, to trigger the robot's emergency stop and to make the robot execute a few other important commands at any time.

Obviously, there are some limitations in our current implementation. One limitation is that not all utterances are allowed, or can be understood, at any moment. The concept of contexts with limited grammar and vocabulary does not allow for a multitude of different utterances for the same topic. Speech recognition is not yet sufficiently advanced to allow a truly unrestricted and human-like communication, and compromises have to be accepted, also in order to enhance recognition in noisy environments. Furthermore, in our implementation it is currently not possible to track a speaker's face, gestures or posture. This would definitely increase the versatility and robustness of human-robot communication.

For more comprehensive information on *HERMES'* communication subsystem see [Bischoff & Graefe 2004].

C. Learning

Learning by doing. Two forms of learning were investigated: autonomous and cooperative learning. They both help the robot to learn by actually doing a useful task: *Autonomous learning* lets the robot automatically acquire or improve skills, e.g., grasping of objects, without quantitatively correct models of its manipulation or visual system. C*ooperative learning* lets the robot generate, or extend, an attributed topological map of the environment over time in cooperation with human teachers.

The general idea to realize *autonomous* learning is simple. While the robot watches its end effector with its cameras, like a playing infant watches his hands with his eyes, it sends more or less arbitrary control commands to its motors. By observing the resulting changes in the camera images it "learns" the relationships between such changes in the images and the control commands that caused them. After having executed a number of test motions the robot is able to move its end effector to any position and orientation in the images that is physically reachable. If, in addition to the end effector, an object is visible in the images, the end effector can be brought to the object in both images and, thus, in the real world.

Based on this concept a robot can localize and grasp objects without any knowledge of its kinematics or its camera parameters. In contrast to other approaches with similar goals, but based on neural nets, no time-consuming training is needed before the manipulation may start [Graefe 1999].

The general idea to realize *cooperative* learning is to let the robot behave like a new worker in an office with the ability to explore, e.g., a network of corridors, and to ask people for reference names of specific points of interest, or to let people explain in natural language how to get to those points of interest. Geometric information is provided by the robot's odometry, and relevant location names are provided by the persons who want the robot to know a place under a specific name. In this way the robot learns quickly how to deliver personal services according to each user's individual desires and preferences, especially: How do (specific) persons call places; what are the most important places and how can one get there; where are objects of personal and general interest located; how should specific objects be grasped? The ability to link, e.g., persons' names to environmental features, requires several databases and links between them in order to obtain the wanted information, e.g., whose office is located where, what objects belong to specific persons and where to find them.

Many types of dialogues exist to *cooperatively* teach the robot new knowledge and to build a common reference frame between a person and the robot for subsequent execution of service tasks. For instance, the robot's lexical and syntactical knowledge bases can easily be extended, firstly, by directly editing them (since they are text files), and secondly, by a dialogue between the robot and a person, that allows to add new words and macro commands during run-time.

To teach the robot names of persons, objects and places that are not yet in the database (and, therefore, cannot be understood by the speech recognition system), a spelling context has been defined that mainly consists of the international spelling alphabet. This alphabet has been optimized for ease of use by humans in noisy environments, such as aircraft, and has proved its effectiveness for our applications as well, although its usage is not as intuitive and natural as individual spelling alphabets or as a more powerful speech recognition engine would be.

VI. EXPERIMENTS AND RESULTS

Since its first public appearance at the Hannover Fair in 1998 where *HERMES* could merely run (but still won "the first service robots' race"!) quite a number of experiments have been carried out that prove the suitability of the proposed methods. Of course, we performed many tests during the development of the various skills and behaviors of the robot and often presented it to visitors in our laboratory. Public presentations made us aware of the fact that the robot needs a large variety of functions and characteristics to be able to cope with the different environmental conditions and to be accepted by the general public.

In all our presentations we experienced that the robot's anthropomorphic shape encourages people to interact with it in a natural way. One of the most promising results of our experiments is that our calibration-free approach [Graefe 2008] seems to pay off, because we experienced drifting of system parameters due to temperature changes or simply wear of parts or aging. These drifts could have produced severe problems, e.g., during object manipulation, had the employed methods relied on exact kinematic modeling and calibration. Since our navigation and manipulation algorithms only rely on qualitatively (not quantitatively) correct information and adapt to parameter changes automatically, the performance of *HERMES* is not affected by such drifts.

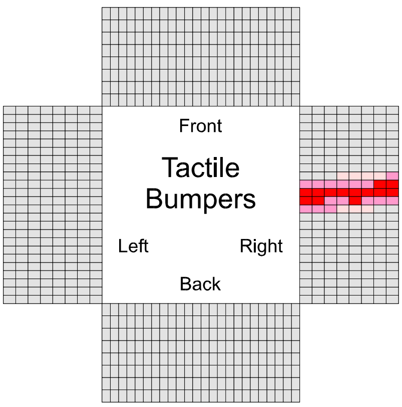

Fig. 13. Sensor image of tactile bumpers after touching the corner of two adjacent walls while the robot was trying to turn around it; color coding: light grey value = no touch, the darker the color the higher the exerted forces during touch; the sensor image outer row to inner row correspond to a covered area from 40 - 320 mm above the ground on the undercarriage.

Cooperative Learning Experiment
In this experiment HERMES and a person are standing in the room commonly referred to as "kitchen". HERMES has been recently introduced to this and some other rooms and only knows a few people so far. It is in a state of waiting for a new instruction within the (default) service context.
Person: "Hello!"
HERMES has to find out who is requesting a service since it is not yet able to recognize people or faces.
***HERMES*: "Hello. My name is *HERMES*. What is your name, please?"**
Person: "My name is Rainer."
HERMES cannot find the person's name in its database, and therefore, switches to the spelling context.
***HERMES*: "I am sorry, but I do not know you. Please spell your name!"**
Person: "Romeo Alpha India November Echo Romeo."
HERMES switches to the confirmation context.
***HERMES*: "Your name is Rainer. Is this correct?"**
Person: "Yes!"
HERMES extends its database of persons and switches back to the service context.
***HERMES*: "Hello Rainer. Pleased to meet you. What can I do for you?"**
Person: "Take this glass. Bring it into my office."
These sentences invoke a number of different skills. First HERMES takes over the glass the person currently holds in his hand. Then, the robot resolves the pronouns "it" and "my" from its situated knowledge. However, the robot does not yet know where the person's office is located. HERMES has to ask the user to provide the missing information.
***HERMES*: "Please describe the way to your office or give me the room number."**
HERMES switches to the navigation context.
Person: "The room number is 2455!"
HERMES switches back to the service context, and starts searching for the room. Alternatively, the person could have given instructions on how to reach the room, such as "Leave the kitchen through the door in front of you. My office is located at the second door to the left!". After having actually found the room, HERMES extends its database of known locations, and marks the room as one of Rainer's offices.

Fig. 14. Excerpt from a dialogue between a human and *HERMES* to transport an object to another room. In its course, *HERMES* learns more about its environment and stores this knowledge in several databases for later reference (e.g., the attributed topological map shown in Figure 15). It should be noted how often contexts are switched, depending on the robot's expectations. This improves the speech recognition considerably.

Tactile sensing also greatly improves the system's dependability. Figure 13 shows an example of the tactile bumper sensors' response in case of an accident. In this simple contact situation *HERMES* tries to continue to deliver its service, e.g., to transport an object, and does not wait until a human has solved the problem. In such a simple case the robot would drive backwards, modify the steering angle and try again. More complex contact situations (2 or more contact locations) still require, for safety reasons, the help of a human.

The dialogue depicted in Figure 14 may serve as an example how *HERMES* and human partner in general may jointly build a common reference frame in their shared working environment in terms preferred by the user. Whenever a command is incomplete (missing command arguments) or ambiguous (too many arguments or imprecise description), a specific dialogue is initiated to resolve the problem. It is important to note that it is always the robot (except in an emergency) who is in charge of the current dialogue and the flow of information towards the user.

Autonomously, or through dialogues with humans, the robot is able to build an attributed topological map of its environment (Figure 15). Since *HERMES* is using only vision for its navigation it is limited by its relatively poor perception (when compared to humans). Nevertheless, the situation-oriented and skill-based system architecture, in addition to the camera's active sensitivity control, enables a navigation performance that is more than adequate for our office building environment. Combined visual and tactile sensing is only in its early stages. We expect the robot to perform even more dependably when these senses are fully integrated and combined.

In the sequel we concentrate on demonstrations that we performed outside the familiar laboratory environment, namely in television studios, at trade fairs and in a museum where *HERMES* was operated by non-experts for an extended period of time. Such demonstrations subject the robot to various kinds of stress. First of all, it might be exposed to rough handling during transportation, but even then it should still function on the set. Second, the pressure of time during recording in a TV studio requires the robot to be dependable; program adaptation or bug-fixing at the location is not possible. *HERMES* performed in TV studios a number of times and we have learned much through these events. We found, for instance, that the humanoid shape and behavior of the robot raise expectations that go beyond its actual capabilities, e.g., the robot is not yet able to act upon a director's command like a real actor (although sometimes expected!). It is through such experiences that scientists get aware of what "ordinary" people expect from robots and how far, sometimes, these expectations are missed.

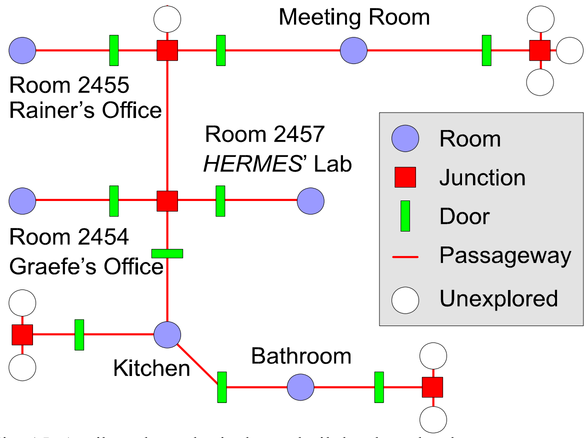

Fig. 15. Attributed topological map built by the robot by autonomous exploration or with help of human teachers through dialogues (e.g., dialogue depicted in Figure 14). The robot learns how persons call (specific) places and how the places are connected via passageways. Multiple names are allowed for individual locations, depending on users' preferences. Geometric information does not have to be accurate for *HERMES'* calibration-free navigation method as long as the topological structure of the network of passageways is preserved. (The map depicted here deviates significantly in complexity, but not in general structure, from the actual map being used for navigation around the laboratory.)

Trade fairs, such as the Hannover Fair, the world's largest industrial fair, pose their challenges, too: Hundreds of moving machines and thousands of people in the same hall make an incredible noise. It was an excellent environment for testing the robustness of *HERMES'* speech recognition system.

Last, but not least, *HERMES* was field-tested for more than 6 months (October 2001 - April 2002) in the Heinz Nixdorf MuseumsForum (HNF) in Paderborn, Germany, the world's largest computer museum. In the special

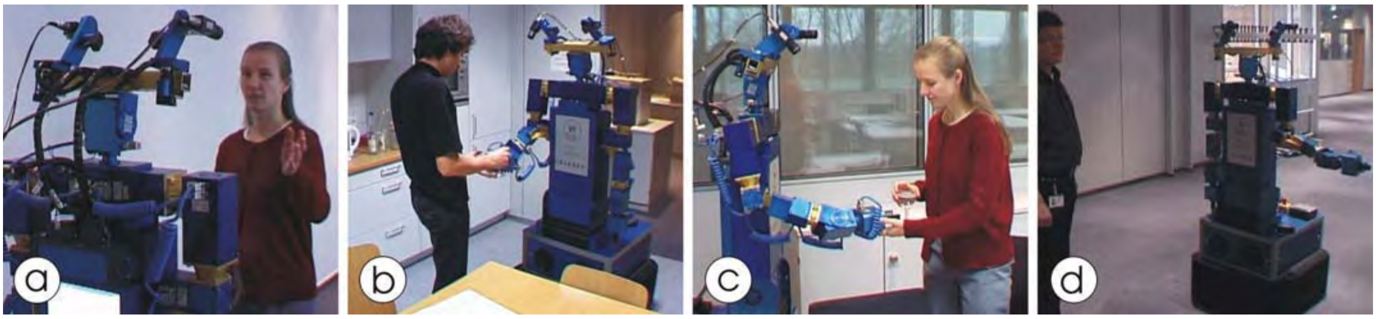

Fig. 16. *HERMES* executing service tasks in the office environment of the Heinz Nixdorf MuseumsForum: (a) dialogue with an a priori unknown person with *HERMES* accepting the command to get a glass of water and to carry it to the person's office; (b) asking a person in the kitchen to hand over a glass of water; (c) taking the water to the person's office and handing it over; (d) showing someone the way to a person's office by combining speech with gestures (head and arm) generated automatically.

exhibition "Computer.Brain" the HNF presented the current state of robotics and artificial intelligence and displayed some of the most interesting robots from international laboratories, including *HERMES*.

To the best of our knowledge only two research groups have ever undertaken long-term experiments with their robots outside their research environments. One, the museum tour guide, Sage, installed by the group of Nourbakhsh at the Carnegie Museum of Natural History in Pittsburgh [Nourbakhsh et al. 1999], and two, the entertaining robots of Fraunhofer IPA [Graf et al. 2000], still working in the entry hall of the telecommunications museum in Berlin. Both projects accumulated valuable experiences in non-expert operation in crowded environments well over a year. Similar tests were carried with the robots RHINO [Burgard et al. 1999] and MINERVA [Thrun et al. 2000], albeit under the supervision of experts and only for a few days.

We used the opportunity of having *HERMES* in an environment different from our laboratory to carry out experiments involving all of its skills, such as vision-guided navigation and map building in a network of corridors; driving to objects and locations of interest; manipulating objects, exchanging them with humans or placing them on tables; kinesthetic and tactile sensing; and detecting, recognizing, tracking and fixating objects while actively controlling the sensitivities of the cameras according to the ever-changing lighting conditions.

HERMES was able to chart the office area of the museum from scratch upon request and delivered services to *a priori* unknown persons (Figure 16). In a guided tour through the exhibition *HERMES* was taught the locations and names of certain exhibits and some explanations relating to them. Subsequently, *HERMES* was able to give tours and explain exhibits to the visitors. *HERMES* chatted with employees and international visitors in three languages (English, French and German). Topics covered in the conversations were the various characteristics of the robot (name, height, weight, age, etc.), exhibits of the museum, and actual information retrieved from the World Wide Web, such as the weather report for a requested city, or current stock values and major national indices.

HERMES even entertained people by waving a flag that had been handed over by a visitor; filling a glass with water from a bottle, driving to a table and placing the glass onto it; playing the visitors' favorite songs and telling jokes that were also retrieved from the Web (Figure 17).

Videos showing *HERMES* (and other robots) in action are available at http://www.unibw.de/robotics/videos/ .

VII. SUMMARY AND CONCLUSIONS

Today's robots are the latest results of an ongoing technical evolution that has progressed over more than 2000 years. It has progressed from mere dreams to automated mechanical animals and dolls of artistic design, to industrial robots and – most recently – to intelligent service and personal robots.

On the basis of modern technology and by integrating various sensor modalities, including vision, touch and hearing, robots may be built that display intelligence and cooperativeness in their behavior and communicate in a user-friendly way. An early example is the experimental humanoid robot *HERMES*, a complex robot designed according to an anthropomorphic model.

The robot is basically constructed from readily available motor modules with standardized and viable mechanical and electrical interfaces. Due to its modular structure, *HERMES* is easy to maintain, which is essential for system dependability. A simple, but powerful skill-based system architecture is the basis for software dependability. It integrates visual, tactile and auditory sensing and various motor skills without relying on quantitatively exact models or accurate calibration. Actively controlling the sensitivities of the cameras makes the robot's vision system robust with respect to varying lighting conditions (albeit not as robust as the human vision system). Consequently, safe navigation and manipulation, even under uncontrolled and sometimes difficult lighting conditions, were realized. A touch-sensitive skin currently covers only the undercarriage, but is in principle applicable to most parts of the robot's surface.

HERMES understands natural language speaker-independently, and can, therefore, be commanded by untrained humans. This concept places high demands on *HERMES'* sensing and information processing, as it requires the robot to perceive situations and to assess them

Fig. 17. HERMES performing at the special exhibition "Computer.Brain", instructed by commands given in natural language by novice robot users: taking over a bottle and a glass from a person (not shown), filling the glass with water from the bottle (a); driving to, and placing the filled glass onto, a table (b); interacting with visitors (here: waving with both arms, visitors wave back!) (c).

in real time. A network of microcontrollers and digital signal processors embedded in a single PC, in combination with the concept of skills for organizing and distributing the execution of tasks efficiently among the processors, is able to meet these demands.

Due to the innate characteristics of the situation-oriented behavior-based approach, *HERMES* is able to cooperate with humans and to accept orders that would be given to a human in a similar way. Human-robot communication is based on speech that is recognized speaker-independently without any prior training of the speaker. A high degree of robustness is obtained due to the concept of situation-dependent invocations of grammar rules and word lists, called "contexts". A kinesthetic sense based on intelligently processing angle encoder values and motor currents greatly facilitates human-robot interaction. It enables the robot to hand over, and take over, objects from a human as well as to smoothly place objects onto tables or other objects.

HERMES interacts dependably with humans and their common living environment. It has shown robust and safe behavior with novice users, e.g., at trade fairs, television studios, in our institute environment, and in a long-term experiment carried out at an exhibition and in a museum's office area.

In summary, *HERMES* can see, hear, speak, and feel, as well as move about, localize itself, build maps and manipulate various objects. In its dialogues and other interactions with humans it appears intelligent, cooperative and friendly. In a long-term test (6 months) at a museum it chatted with visitors in natural language in German, English and French, answered questions and performed services as requested by them. There might be other research groups that have been carrying out similar experiments, but the fact that those experiments have not been reported on major conferences shows that integration and dependability issues as well as long-term experiments are not yet considered as major problems, neither in the robotics research community nor by the funding agencies or bodies. Also, the few projects listed above focused primarily on navigation and more or less simple human-robot communication.

Although *HERMES* is not as competent as the robots we know from science fiction movies, the combination of all before-mentioned characteristics makes it rather unique among today's *real* robots. While today's robots are mostly strong with respect to a single functionality, e.g., navigation or manipulation, the results achieved with *HERMES* illustrate that many functions can be integrated within one single robot through a unifying situation-oriented behavior-based system architecture. Moreover, they suggest that testing a robot in various environmental settings, both short- and long-term, with non-experts having different needs and different intellectual, cultural and social backgrounds, is enormously beneficial for learning the lessons that will eventually enable us to build dependable personal robots.

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