Demonstrating the Humanoid Robot *HERMES* at an Exhibition: A Long-Term Dependability Test

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Abstract

HERMES, a laboratory prototype of a humanoid service robot, served in a museum, far away from its home laboratory, for more than six months up to 18 hours per day. During this period the robot and its skills were regularly demonstrated to the public by non-expert presenters. Also, HERMES interacted with the visitors, chatted with them in English, French and German, answered questions and performed services as requested by them. Only three major failures occurred during the 6-months-period, all of them caused by failures of commercially available modules that could easily be replaced.

Key to this success was the dependability that had been designed into HERMES. We introduce the concept of dependability and describe the design strategies that have led to a high degree of dependability of our robot. To be accepted by society and to be entrusted with important or even critical services, future service robots must be similarly dependable as today's cars or telephones. We argue that true dependability of complex intelligent robots can only be achieved by actually building and integrating prototypes and subjecting them to long-term tests with outsiders and away from their home laboratories. In fact, by demonstrating HERMES in the museum, at trade fairs and in TV studios we have learned valuable lessons, especially regarding the interaction of a complex service robot with unknown humans.

1 Introduction

Exhibitions offer excellent opportunities for studying and evaluating a robot's communication skills and dependability under real-world conditions, especially if the robot is exposed to the public, and allowed to interact with it, for extended periods of time. However, to have a chance of surviving such a long-term test at an exhibition without annoying failures, a robot must be much more dependable than a typical research robot in a laboratory.

This requirement is probably the reason that, to the best of our knowledge, only two research groups have ever undertaken long-term experiments with their robots interacting with strangers outside their own laboratories. 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 experience in non-expert operation in a crowded environment well over a year. During the World Exposition 2000 in Hannover, 72 mobile robots (size 1.6 to 4.5 meters) were constantly moving freely on a surface of 5000 m^2 with speeds up to 0.25 m/s while reacting to the presence of visitors and coordinating themselves in relation to each other [BBM Expo 2000]. Unfortunately, up to date we have not become aware of any scientific report on this experiment. Similar tests were carried out by Thrun and Burgard 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. Long-term experiments with mobile robots in their respective institute environments were carried out by [Simmons et al. 1999] at the Robotics Institute (CMU, Pittsburgh) with the robot XAVIER, one of the first mobile robots controllable via a Web interface, and by a research group at the Institute of Robotics (ETH, Zürich) with a mobile mail distribution system called MOPS [Tschichold et al. 2001]. Commercially available robots that do not possess complex interaction interfaces, but are nonetheless easy to operate and have been exposed to a general public, are the Helpmate robot [King, Weiman 1990], that was installed in dozens of hospitals world-wide, and a cleaning machine equipped with a Siemens Corporation navigation system, still working in a supermarket in the Netherlands [Endres et al. 1998].

There might be other groups that have been carrying out similar experiments, but the fact that those experiments have not been reported at major conferences shows that integration and dependability issues as well as long-term experiments are not yet considered important and interesting problems, neither in the robotics research community nor by the funding agencies or bodies. Also, the projects listed above focused primarily on navigation and more or less simple human-robot communication (more complex in case of MINERVA and RHINO). – We wonder if service or personal robots will ever become valuable servants of our future society if not more robots are fielded for extended periods of time with a richer set of functionalities, a higher level of human-robot interaction and in realistic settings.

As we pointed out before, dependability is crucial for a robot to be able to serve at an exhibition, and also for future personal and service robots to be accepted by society. "Dependability" is a system concept that integrates such attributes as reliability, availability, safety, confidentiality, integrity, and maintainability [Laprie 1992]. The goals behind the concept of dependability are the abilities of a system to deliver a service that can justifiably be trusted and to avoid failures that are more frequent or more severe, and outage durations that are longer, than is acceptable to the user(s).

Our society largely depends on infrastructures that are controlled by embedded information systems and the dependability concept has been widely employed for such systems. Although future service and personal robots are supposed to become an important part of our future society, dependability aspects have been largely neglected by researchers. However, dependability is needed especially for these types of robots because they are intended to operate in unpredictable and unsupervised environments and in close proximity to, or in direct contact with, people who are not necessarily interested in them, or, even worse, who try to harm them by disabling sensors or playing tricks on them.

Figure 1: Humanoid experimental robot *HERMES*; 1.85 m x 0.7 m x 0.7 m; mass: 250 kg

It is one aim of this paper to raise the awareness for research on integration and dependability, and for long-term experiments. There is no other way to increase the dependability of service robots in the long run.

2 Designing for Dependability

In our opinion the dependability of a robot is not something that can be added on after the robot has been designed and built. Rather, it must be designed into the robot and, specifically, it emerges from the following design strategies:

1. Learning from nature how to design reliable, robust and safe systems
2. Providing natural and intuitive communication and interaction between the robot and its environment
3. Designing for ease of maintenance
4. Striving for a tidy appearance

These design strategies have guided us in the design and construction of our humanoid robot *HERMES* (Figure 1). They are explained in greater detail in the sequel.

Learning from nature. According to the classic approach, robot control is model-based. Numerical models of the kinematics and dynamics of the robot and of the external objects that the robot should interact with, as well as quantitative sensor models, are the basis for controlling the robot's motions. The main advantage of model-based control is that it lends itself to the application of classical control theory and, thus, may be considered a straightforward approach. The weak point of the approach is that it breaks down when there is no accurate quantitative agreement between reality and the models. Differences between models and reality may come about easily; an error in just one of the many coefficients that are part of the numerical models can suffice.

Organisms, on the other hand, are robust and adapt easily to changes of their own conditions and of the environment. They never need any calibration, and they normally do not know the values of any parameters related to the characteristics of their "sensors" or "actuators". Obviously, they do not suffer from the shortcomings of model-based control which leads us to the assumption that they use something other than quantitative measurements and numerical models for controlling their motions. Perhaps their motion control is based on a holistic assessment of situations for the selection of behaviors to be executed. Possibly robotics could benefit from following a similar approach.

Following this line of argumentation we strongly believe that sensing in general should be based on the senses that have proved their effectiveness in nature. Therefore, vision – the sensor modality that predominates in nature – is also an eminently useful and practical sensor modality for robots. Also, tactile sensing and hearing may greatly improve a robot's safe operation as shown by nature.

Providing natural and intuitive communication and interaction. Any person who might encounter a service robot needs to be able to communicate and interact with it in a natural and intuitive way. Therefore, the communication interface has to be designed in such a way that no training would be required for any person who might get in contact with the robot. This can be achieved if the human-robot communication resembles a dialogue that could as well take place between two humans.

Designing for ease of maintenance. The first step to make a complex system dependable is to make its components reliable. Moreover, we believe that only a robot that needs little or no maintenance and that can be easily repaired (if ever needed) will be accepted as a co-worker, caretaker or companion.

Striving for a tidy appearance. It is a matter of personal experience that, especially in research environments, robots often fail because of broken cables and unreliable connections. Such robots often look very cluttered with cables criss-crossing each other, and circuitry and connectors hidden under bundles of wires. This not only makes visual inspection difficult, but it may also be taken as an indication that those who built and maintain the robot have placed little emphasis on a systematic design. Although software is not visible, the observer wonders whether the structure of the robot's software might resemble the layout of the robot’s wiring.

3 The Humanoid Robot *HERMES*

In designing our humanoid experimental robot *HERMES* we placed great emphasis on modularity and extensibility of both hardware and software [Bischoff 1997].

3.1 Hardware

HERMES has an omnidirectional undercarriage with 4 wheels, arranged on the centers of the sides of its base. 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°). The work space extends up to 120 cm in front of the robot. Currently 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 in addition to the pan/tilt unit that controls the common “head” platform. The cameras can be moved with accelerations and velocities comparable to those of the human eye.

HERMES is built from 25 drive modules with identical electrical and similar mechanical interfaces yielding 22 degrees of freedom. Each module contains a motor, a Harmonic Drive gear, a micro-controller, power electronics, a communication interface and some sensors. The modules are connected to each other and to the main computer by a single bus.

A hierarchical multi-processor system is used for information processing and robot control (Figure 2). 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 320C40) embedded in a ruggedized, but otherwise standard industrial PC. Sensor data processing (including vision), situation recognition, behavior selection and high-level motion control are performed by the DSPs, while the PC provides data storage, Internet connection and the human interface.

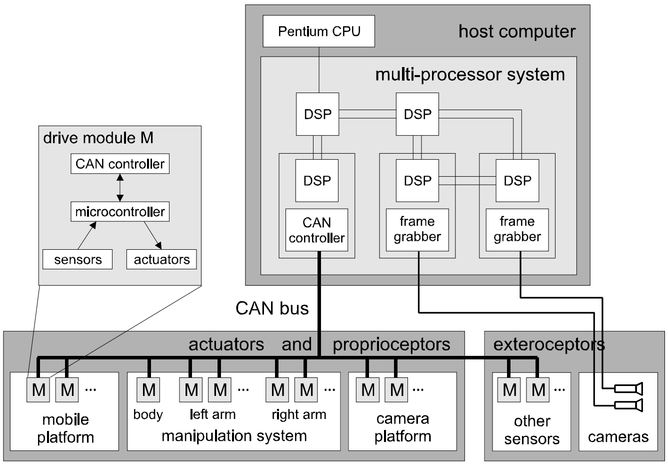

Figure 2: Modular and adaptable hardware architecture for information processing and robot control.

3.2 Software and System Architecture

Seamless integration of many – partly redundant – degrees of freedom 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 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 3 shows the essence of the situation-oriented behavior-based robot architecture as we 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 other hardware components – sensors, actuators, knowledge base storage and MMI (man-machine, machine-machine interface) peripherals.

These skills have direct access to the hardware components and, thus, actually realize behavior primitives. 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. 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.

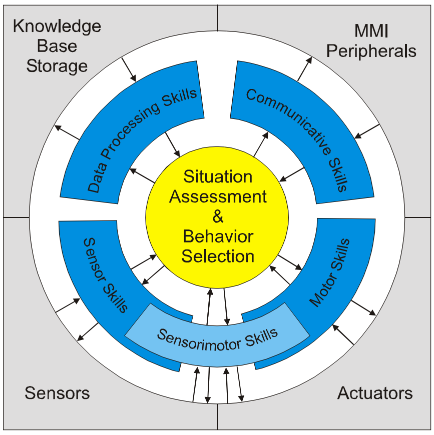

Figure 3: System architecture of a personal robot based on the concepts of situation, behavior and skill.

The situation module fuses via skills data and information from all system components to make situation assessment and behavior selection possible. Moreover, it provides general system management (cognitive skills). Therefore, it is responsible for planning an appropriate behavior sequence to reach a given goal, i.e., it has to coordinate and initialize 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 leads to complex and elaborate robot behavior. For a more profound discussion of our system architecture which bases upon the concepts of situation, behavior and skill see [Bischoff, Graefe 1999].

Several of the fundamental concepts developed at our Institute were implemented in *HERMES* and contribute to its remarkable dependability: 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]. Also, the sensitivities of the cameras can be individually controlled for each object or image feature, and several forms of learning assure adaptation to changing system parameters as well as working in new environments from scratch. Moreover, a speaker-independent speech recognition for several languages and robust dialogues form the basis for various kinds of human-robot interaction [Bischoff , Graefe 2002].

4 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. The 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 have experienced that the robot’s anthropomorphic shape encourages people to interact with it in a natural way. As presented in the preceding sections, *HERMES* possesses several other promising features inside and outside that makes it intrinsically more reliable and safer than other robots. One of the most promising results of our experiments is that our calibration-free approach 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, if 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.

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, e.g., in television studios, subjects 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* has 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.

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

We used the opportunity of having *HERMES* in a different environment 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 4). 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, ...), 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 5).

5 Lessons Learned

We found it interesting to observe how *HERMES*, actually just a laboratory prototype despite its designed-in dependability, survived the daily hard work far away from its "fathers", where no easy access to repair and maintenance was available, and how it got along with strangers and even with presenters who did not know much about robot technology. In fact, we were surprised ourselves that it performed so well. During 6 months of operation (lasting up to 18 hours a day during video recordings for documentation purposes) only one motor controller, one drive motor and one audio amplifier ceased to function, all of them commercially available and easily replaceable. According to the museum staff, *HERMES* was one of the few robots at the show that could regularly be demonstrated in action, and among them it is considered the most intelligent and most dependable one. This statement is supported by the fact that the museum staff never called for advice once the initial setup was done. We had expected to give much more support and wondered how often we would have to travel from Munich to Paderborn (a six-hour-drive, one way) to help. Actually, we only were in Paderborn for setting up the robot for the exhibition, for presenting and documenting our research work during the first two weeks after the exhibition's opening and for 4 days of documentation work in December.

Preparing the robot for the exhibition was indeed fun, but also a lot of work: it made us realize that many operational details had never been documented before, such as powering the robot on and off, charging the batteries, starting the main program and testing functionality. Now they had to be written down in a manual for non-experts, i.e., people with little engineering background. Actually, the museum staff had insisted on having such a reference guide, but as a matter of fact, it shared the fate of most reference manuals in the world: it was almost never looked at, because people rather like to try out how things work instead of studying manuals, which makes the need for safe behavior even more evident.

Being afraid that the robot might come back to our university in pieces, we had made an effort to finish many of the laboratory's research projects before sending *HERMES* to the museum. Actually, such time pressure helped to speed up work on algorithms and implementation details.

Although we knew that thorough testing is only possible in different environments with numerous different people interacting with the robot, we had never before really been able to do so over an extended period of time. This exhibition gave us the opportunity, and eventually, it proved that our concepts and approaches (as presented

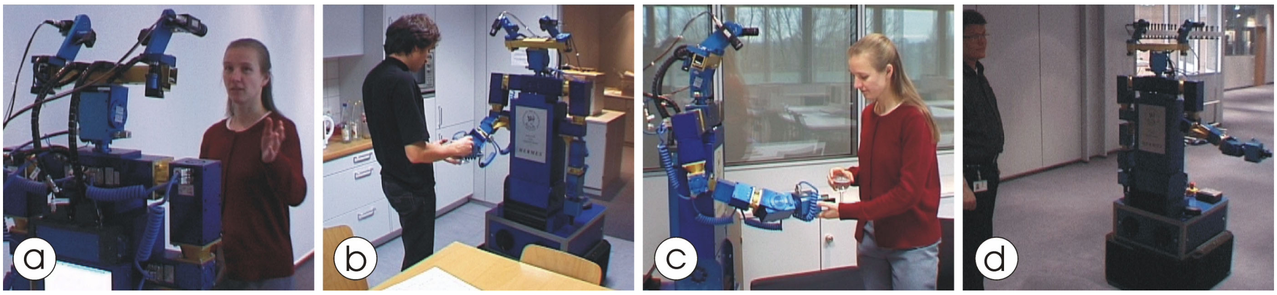

Figure 4: *HERMES* executing service tasks in the office environment of the Heinz Nixdorf MuseumsForum: (a) dialogue with an *a priori* unknown person with *HERMES* accepting the command to get a glass of water and to carry it to the person's office; (b) asking a person in the kitchen to hand over a 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.

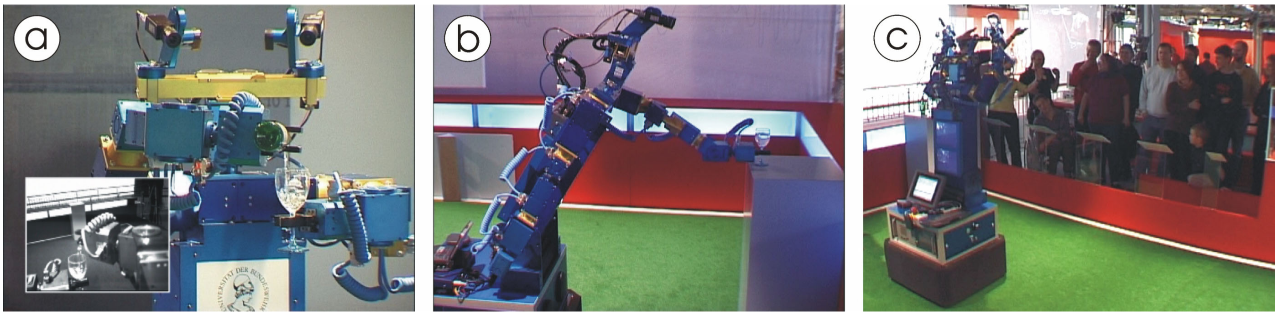

Figure 5: *HERMES* performing at the special exhibition “Computer.Brain”, instructed by natural language commands: taking over a bottle and a glass from a person (not shown), filling the glass with water from the bottle (a); driving to and placing the filled glass onto a table (b); interacting with the visitors (here: waving with both arms, visitors wave back!) (c)

in chapters 2 and 3) were correct. Consequently, to *really* see the robot working in a completely different environment, operated by non-experts for over 6 months, was certainly the most valuable experience of this long-term experiment. Some behaviors worked much better in the new environment than in our institute, others worse. For example, navigation worked much better on the one hand because the floor was not as reflective as our institute’s floor. On the other hand, the overall lighting conditions were rather poor and in the actual exhibition area it was almost too dark to navigate by means of vision. Although a large part of the exhibition featured red and yellow walls and a grey floor, it was very difficult for our monochrome vision system to distinguish between walls and floors. A color vision and a higher dynamic range of the cameras would certainly be desirable for our robot.

Especially children liked interacting with the robot. Surprisingly enough, the robot could understand the children’s high voices and sometimes not fluently spoken phrases. They even hugged the robot, albeit under close supervision of the staff, without being afraid of breaking something, and, much more important, being afraid of being hurt by such a massive chunk of moving metal. Adults, on the other hand, faced the robot with all due respect.

Some people pushed the robot’s emergency button that was clearly visible in the back of the robot, and expected something to happen. Since the emergency button only disconnects the motors from the power but not the computers, a lengthy reboot procedure was not required. The staff just had to pull up the emergency button again to restart the robot. We know now that the state of the emergency button should be monitored by the robot in order to react adequately to such a situation.

The funniest interaction for most of the visitors and the staff alike resulted from touching the tactile bumpers placed around the robot’s undercarriage. The robot was programmed to stop moving and to say “Ouch”. This simple “emotion” made most of the people smile, and kept them touching the bumpers more than once. On the other hand, behaviors that the developers considered more impressive, such as navigation and manipulation, were taken for granted. The interaction capabilities on top of assumed (normal) behavior is what most people are interested in. Certainly, this does not simplify the robot scientist’s work since his robots obviously have to “compete” with the well-known robots from science fiction movies.

According to a museum press release, more than 80.000 visitors had been attracted by the special exhibition “Computer.Brain” which was 30.000 more than had been hoped for. The maximum capacity of the museum was reached on several days, leading to long waiting lines. This tremendous success is certainly due to the highly interactive character of the exhibition. Of the 330 exhibits 52 were interactive, the most spectacular ones being robots. The overall exhibition’s media presence was remarkable with 18 independent broadcasts in televison (not counting reruns) and 11 in the radio, in addition to an uncountable number of newspaper articles. Taking media presence as an important indicator for successful and well recognized work, our project was indeed quite successful: to our knowledge *HERMES* was featured to a larger extent at least 6 times in TV, twice in radio and 18 times in newspaper articles (most of them during the two weeks after the exhibition’s opening).

6 Summary and Conclusions

HERMES, an experimental robot of anthropomorphic size and shape, interacts dependably with people and their common living environment. It has shown robust and safe behavior with novice users, e.g., at trade fairs, television studios, at various demonstrations in our institute environment, and in a long-term experiment carried out at an exhibition and in a museum’s office area. The robot is basically constructed from readily available motor modules with standardized and viable mechanical and electrical interfaces. Due to its modular structure the robot 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 CCD 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 spoken natural language speaker-independently, and can, therefore, be commanded by untrained humans.

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.

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. As noted in the introduction, today's robots are mostly strong with respect to a single functionality, e.g., navigation or manipulation. Our results illustrate that many functionalities can be integrated within one single robot through a unifying situation-oriented behavior-based system architecture. We also believe that our simple design strategies, such as modularity, calibration-free control and truly human-like interaction, would enable other researchers, too, to build similarly dependable robots. Our results 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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