Humanoids and Personal Robots: Design and Experiments

Paolo Dario,∗ Eugenio Guglielmelli, and Cecilia Laschi
ARTS Lab
Scuola Superiore Sant’Anna
Pisa, Italy

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This paper addresses the field of humanoid and personal robotics—its objectives, motivations, and technical problems. The approach described in the paper is based on the analysis of humanoid and personal robots as an evolution from industrial to advanced and service robotics driven by the need for helpful machines, as well as a synthesis of the dream of replicating humans.

The first part of the paper describes the development of anthropomorphic components for humanoid robots, with particular regard to anthropomorphic sensors for vision and touch, an eight-d.o.f. arm, a three-fingered hand with sensorized fingertips, and control schemes for grasping. Then, the authors propose a user-oriented design methodology for personal robots, and describe their experience in the design, development, and validation of a real personal robot composed of a mobile unit integrating some of the anthropomorphic components introduced previously and aimed at operating in a distributed working environment.

Based on the analysis of experimental results, the authors conclude that humanoid robotics is a tremendous and attractive technical and scientific challenge for robotics research. The real utility of humanoids has still to be demonstrated, but personal assistance can be envisaged as a promising application domain. Personal robotics also poses difficult technical problems, especially related to the need for achieving adequate safety, proper human–robot interaction, useful performance, and affordable cost. When these problems are solved, personal robots will have an excellent chance for significant application opportunities, especially if integrated into future home automation systems, and if supported by the availability of humanoid robots.

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∗To whom all correspondence should be addressed; e-mail: dario@arts.sssup.it; http://www-arts.sssup.it

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1. INTRODUCTION

In the history of human endeavor, two recurrent objectives have inspired the "engineers" who designed machines: the dream of developing humanlike machines ("humanoids"), which aimed at replicating human functions, shape, and even reasoning, and the need to implement useful machines that could help human beings in real-life conditions and alleviate their (often hard) working conditions. The first dream was hampered by many obstacles, including ethical, religious, and psychological concerns, but especially by the limitations of technology, which allowed, at best, isolated demonstrations of virtuosity. (These were sometimes quite impressive, as in the case of the mechanical automata developed in Switzerland in the eighteenth century, able to automatically write or play the piano.) On the other hand, the design of useful machines, not necessarily anthropomorphic, was always pursued more aggressively, obviously with fewer nontechnical concerns and with results that were limited only by technology. Automation and industrial robotics are relatively recent results of this line of evolution.

More recently, the progress of robotics technology, on the one hand, and the growing social importance in the industrialized countries of the expectations and needs of the disabled and elderly, on the other, have spurred the development of a new field of research and industrial application, known as "personal robotics", whose objective is to implement intelligent machines capable of assisting human beings in many practical circumstances. There is now a wide consensus in the robotics research community that personal robotics will be a "grand challenge" for the next millennium. Service robotics evolved from industrial robotics with the contribution of visionary scientists, and mostly in the framework of large scale projects. Service is a large application domain that poses several problems to robotics, since flexible operational capabilities in nonstructured environments are typically requested of service robots. However, an increasing number of applications investigated for service robots imply assistance to and cooperation with human beings in many different real-life scenarios.

In classical applications for industrial automation, the environment is typically structured based on the robot capabilities and the application requirements; in more advanced application domains, such as space and underwater scenarios, the environment can be partially or completely unstructured. Service robots must work into environments modeled on human needs, that can seldom be structured for them, and in which humans can be present, so that the problem of safe human-robot interaction arises. This important requirement was addressed by some investigators who referred to the concept of "human-friendly service robots." These robots exploit cooperation with humans for the execution of many useful tasks, yet guaranteeing safe interaction.

Personal robotics is the final step in this evolution; it introduces the notion of the "personal use" of the robot in many specific tasks, and in particular for assistance to the disabled and the elderly. Personal robotics is rapidly evolving from the initial idea of an "anthropomorphic robotic servant," often proposed by science fiction, into a number of different possible configurations, ranging from the completely autonomous robots to smart mechatronic assistive devices and distributed interfaces, and to the development of a new generation of real humanoids. Several important scientific events, such as the IEEE Robotics and Automation Conferences, have included panels and workshops on the theme of the personal robot. These events have also been devoted by leading associations, such as the IARP (G7 International Advanced Robotics Program) and the Japan Robotics Society, to the promotion of this research field; for example, the organization of the First Symposium on Humanoid Robots (HURO) in 1996, the IARP First Symposium on Service and Personal Robots in 1997, the First IARP International Workshop on Humanoid and Human-Friendly Robotics in 1998, and the IARP-US/Europe Workshop on Personal Robotics in 1999.

Is the implementation of human behavioral schemes and the replication of anthropomorphic physical appearance the real answer in every context for the development of helpful machines for personal use? This question, which is still open in the...
current scientific debate, 14, 42 will be addressed in this paper.

The paper proposes an overall framework for research on humanoids and personal robots, and provides a detailed description of recent efforts by the authors in the implementation of working prototypes of standalone components, behavioral control schemes, and integrated systems. Furthermore, it presents an actual case study of a personal robotic assistant for the disabled and elderly at home, reporting experimental results from direct validation in daily-life situations with humans, and eventually describing guidelines and lessons learned, which are probably of general interest for future developments of personal robotics.

The paper is organized as follows: Section 2 introduces the proposed general scheme for artificial perception, and describes the anthropomorphic components (such as sensors, actuators, and control schemes) developed in our laboratory; Section 3 describes the proposed framework for the personal robot, and some methodological guidelines for its development; Section 4 describes the implementation of a prototype personal robot aimed at testing with real users some of the components described in Section 2 and the guidelines described in Section 3; and Section 5 summarizes the main achievements of our research and outlines our viewpoint for the future development of humanoids and personal robots.

2. AN ANTHROPOMORPHIC APPROACH TO ARTIFICIAL PERCEPTION AND SENSORY-MOTOR COORDINATION IN ROBOTICS

Research in anthropomorphic robotics has traditionally pursued a twofold objective:

1. Validation of bioengineering models, so as to increase knowledge of biological subsystems. The idea
pursued by some scientists along this line is to develop a physical model, both at the level of sensors and actuators and at the level of sensory data processing, sensory-motor coordination, and behavioral schemes, implementing and validating bioengineering models. The approximations introduced by the physical model represent possible critical factors of this approach and thus its viability has yet to be fully demonstrated.

2. Replicating humans. The idea is to develop robots that have a biomorphic appearance and are able to behave like humans. In this direction, likewise, the real potential for usefulness of such robots has yet to be demonstrated.

These two research lines are closely related. In most cases the challenge of designing and developing a humanoid implies necessarily the study of anthropomorphic components, such as sensory systems and actuators, and of learning and reasoning paradigms, such as behavior synthesis and generation. The feasibility and performance of humanoid robots depend intrinsically on the availability of suitable sensors, actuators, and control schemes.

In artificial perception, anthropomorphism is important both in the sensing device and in the models for processing sensory data. A possible anthropomorphic scheme for artificial perception and sensory-motor coordination is proposed in ref. 76, and used as a guideline for the developments presented by the authors in this paper. Vision and touch are the most important perceptual modalities in humans and thus the most important to be replicated in robots for artificial sensory-motor coordination. Tactile exteroceptive perception (including measurements of pressure distribution, temperature and material thermal properties, texture, and contact force/torque) and proprioception of arm and hand configurations are all fused in “haptic perception.” The paradigm of active perception is assumed in the anthropomorphic model for artificial perception. Our approach to the development of the processing module starts from the assumption that two different kinds of processing can be replicated from the human model: low-level and high-level processing.

Low-level processing is the fusion and interpretation of perceptual data with no involvement of conscious cognitive processes. In contrast, high-level processing involves conscious cognitive processes in the understanding of perceived data and in the planning of appropriate behavior. Learning is a fundamental feature at both levels, allowing proper functioning of each module.

In the proposed scheme, anthropomorphic actuators, such as arms and hands, provide proper tools for interaction with the environment. Different tasks that include sensory integration and data processing (such as grasping, manipulation, and recognition) can be identified as important for personal robotic applications, and as good examples of how low-level and high-level processing are involved in sensory-motor coordination. Whereas grasping can be considered essentially a low-level task, and manipulation a high-level task, recognition has a twofold nature. When grasping an object, the hand is configured to fit the object’s shape, and grasping force is tuned to the object’s physical features. In humans this strategy is implemented instinctively through low-level processing, with no particular conscious effort. In contrast, manipulative actions, such as writing, opening a door, or pouring water from a bottle, require a varying involvement of conscious attention. Recognition occurs at different levels: the feeling from the contact with an object’s surface provides the perception of the material the object is composed of, without conscious reasoning on thermal properties, texture, or stiffness. On the other hand, unknown objects require a deeper analysis to be recognized, involving high-level reasoning.

In the proposed scheme, anthropomorphism can be implemented at different levels. First of all, the choice of sensors and actuators must guarantee that perceptual data and motor actions can replicate, to some extent, those of humans. Further, the computing techniques used for the low- and high-level processing modules should be able to replicate some of the features of human reasoning.

The scheme just outlined has been implemented and validated on different experimental platforms. These platforms comprise: 1) two anthropomorphic sensors: a retinalike visual sensor, and an integrated fingertip with tactile sensors; 2) two actuators, such as arms and hands, provide proper tools for interaction with the environment. Different tasks that include sensory integration and data processing (such as grasping, manipulation, and recognition) can be identified as important for personal robotic applications, and as good examples of how low-level and high-level processing are involved in sensory-motor coordination.
resulting image.\textsuperscript{95} Space-variant resolution reduces drastically the amount of data in a single image, at the cost of a degradation of the peripheral areas of the image.

In addition to replicating different human tactile capabilities (contact, pressure, dynamic, thermal, proprioceptive) by means of suitable sensors, achieving anthropomorphic tactile perception requires the integration of the different sensors into a miniaturized support, as in the human skin, and the fusion of different sensory exteroceptive and proprioceptive data into one perception.\textsuperscript{24,25,65} With this aim, an integrated miniature fingertip has been developed at the ARTS Lab, with support from KIST (Korean Institute of Science and Technology, Seoul, Korea), for application in dexterous hands.\textsuperscript{39,79,107} Different sensors (a space-variant array of 64 piezoresistive contact sensors; a piezoelectric element dynamic sensor; and a thermistor-based sensor) have been integrated into one sensory system, including miniaturized preprocessing and control electronics, so as to be assembled in an anthropomorphic fingertip, with sensors on the external surface and processing electronics inside. The resulting system is an integrated anthropomorphic smart fingertip with contact, dynamic, and thermal sensory capabilities and data acquisition functionality.

2.2. Anthropomorphic Actuators

Present technology is still far from offering actuating performances comparable to those of human muscle, even though interesting examples of “pseudo-muscles” have been developed using traditional\textsuperscript{64} and innovative technologies.\textsuperscript{12,17,19,49,56}

At a higher level, anthropomorphism can be envisaged in robotic limbs, such as arms, hands, legs, and so on.\textsuperscript{61,84} As an experimental platform, we used the eight-d.o.f. anthropomorphic arm (“Dexter Arm,” S. M. Scienzia Machinale srl, Pisa, Italy) developed for incorporation in the URMAD service robotic system described in ref. 28. Though no anthropomorphic actuation solutions were exploited in the Dexter Arm, its physical structure is highly anthropomorphic, as shown in Figure 2(a). Cable transmission was adopted for the actuation of joint movements, and the links structure reproduces the human body from trunk to wrist. The arm was equipped with a two-d.o.f. three-finger hand (the “Marcus Hand,” shown in Figure 2(b)) featuring an opposing thumb, originally designed as a human prosthesis and then used also for robotic applications.\textsuperscript{97} The Marcus Hand has good grasping capabilities in terms of the set of graspable objects, size, and grip force. A passive mechanical system allows to fit the prosthesis kinematic configuration to the object, and force and slip-detection sensors

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{(a) The eight-d.o.f. Dexter Arm, and (b) the three-finger, two-d.o.f. Marcus Hand, both manufactured by S.M. Scienzia Machinale srl, Pisa, Italy.}
\end{figure}
in its fingertips and palm allow it to control grasping. In addition, the integrated fingertip described in Section 2.1 was incorporated in the thumb of the hand for experiments on tactile perception. Our laboratory is currently developing a new anthropomorphic hand using a biomechatronic design.

2.3. Anthropomorphic Computing Techniques

Replicating the functionality of the human brain is one of the hardest challenges in anthropomorphic robotics and in general still one of the most distant objectives. However, initial attempts can be made in the replication of some well-identified processes of the human brain, especially in artificial perception and sensory-motor coordination.

Traditional computing techniques, based on the classical sequentiality of computer elaboration, hardly fit the basic features of human brain processes. More recent computing paradigms, such as neural networks and fuzzy logic, provide more suitable tools for anthropomorphic processing modules.

A number of observations suggest the usefulness of neural computing techniques in the low-level processing of sensory data in robotics:

- the processing performed by neural networks is achieved thanks to the connections in the nodes of the network, just as low-level processing in humans is performed by physical connections among neurons;
- information is processed by neural networks in parallel, as sensory data are perceived simultaneously and fused in human multisensory perception;
- one of the main features of a neural network is the plasticity and adaptability of the structure, where connections among nodes can be modified dynamically, in the same way they are reinforced or cancelled in the human brain;
- neural networks are generally redundant and guarantee the production of output values even if some units or connections are missing, by applying the same solution found in animals, based on redundancy;
- finally, the concept of learning is intrinsically related to artificial neural networks, just as learning is intrinsic in human mental processing.

Recently, a new learning paradigm inspired by the psychological aspects of human learning, called “Reinforcement Learning,” was developed by Sutton. In the reinforcement learning paradigm, the system must emulate an expected behavior without a direct specification of the output, and having as feedback from the environment only a scalar value representing how well the action was performed in response to a particular input. Reinforcement Learning is learning about, from, and while interacting with an environment in order to achieve a goal. In other words, reinforcement learning is a model of learning in humans and animals plausible both from a neurophysiological (Hebbian rule) and a psychological (Pavlovian conditioning) point of view.

Fuzzy logic has been successfully applied to control systems in which a mathematical model of processes is not required, but for which qualitative algorithms are well suited. Fuzzy control systems are knowledge-based, and thus are particularly well suited when knowledge is available regarding the expected process behavior. In the approach outlined in this paper, we focused on the implementation of low-level processing and learning, based on a neural approach integrated with fuzzy logic and a variety of learning paradigms (namely supervised, unsupervised, and reinforcement learning paradigms).

2.4. Experiments on Anthropomorphic Artificial Perception and Sensory-Motor Coordination in Robotic Grasping

In our laboratory, the different aspects related to the development of proper paradigms for artificial perception and sensory-motor coordination in robotic manipulation have been approached in a modular integrated framework, so that the various solutions can be combined as the many pieces of a complete mosaic. In detail, four modular solutions for the following identified issues were developed:

1. planning of the proper hand configuration for grasping, based on rough geometrical information on the object to be grasped, through a neuro-fuzzy approach;
2. integration of visual and tactile feedback for the coordination of hand motor actions on the object surface, through a reinforcement learning-based neural system;
3. haptic-motor coordination of the fingers for stable grasping, through a neural system replicating a well-known model of a part of the primary cortex; and
4. integration of visual and tactile information for recognition of object material before manipulation, through a self-organizing neural system.
The details of the implementation of the four solutions and the achieved results are given in refs. 76, 77, 81, and 108. A project in progress is the implementation onto a robotic platform of models of the areas of the human brain involved in grasping.109

3. DESIGN AND DEVELOPMENT OF PERSONAL ROBOTS

The concept of the personal robot introduces the idea of the personal use of a robotic machine. Thus, the new issue of acceptability of the proposed technology to the end user emerges dramatically in the design of personal robots.38,42

The usual goal of robotics researchers is to design and build machines able to accomplish some tasks in the production of final products or services. In personal robotics, instead, the researcher is developing directly the final product; thus, new factors typical of product engineering processes (such as task analysis, marketing, industrial design, reliability, and safety) must be included in the design phase. Whereas the performance of industrial robots can be measured by means of objective parameters, the success of a personal robot should be evaluated by applying subjective, user-based criteria. This consideration motivates the increasing use of design evaluation tools borrowed from mass-market production (the performance of a personal robot can be evaluated in almost the same way as a home appliance).

The acceptability of a new product actually includes a number of factors, such as usefulness, pleasure of interaction, safety, and cost, among others.38 Usefulness is strictly related to the tasks the robot can accomplish with respect to the real needs of the end user. Functional specifications must be defined on the basis of well-identified user needs, by following a user-oriented approach in the design phase. Continuous feedback from the end user is a fundamental part of the design and development process rather than a simple verification step. The role of user involvement is, on the one hand, to define the acceptability of the product before the design and, on the other hand, to verify the efficiency of the system after the design.

According to the user-oriented approach, user involvement is repeated at different stages. As a first step, user needs are collected and analyzed, a functional and an anthropological definition of the user are given, and then user requirements are extracted. From user requirements, the preliminary (functional) design specifications can be defined. At this point, user involvement is repeated in order to validate the specifications and get further indications for successive steps of design. A tool for collecting user feedback on the preliminary design is needed, such as a simulation of the system, in the form of drawings, photographs, computer graphics animations, or the like. The preliminary design loop can be repeated several times, until the final system design guidelines are achieved. Final design guidelines allow the development of the first prototype, which is then utilized in the final session of user involvement, user trials. An additional loop is introduced at this stage, which leads to the final system.

The pleasure of interaction with a personal robot is related to the identification of a key metaphor. The widespread adoption of personal computers in the workplace actually occurred when the metaphor of a desktop with folders and working tools was proposed. Perhaps this is the reason that personal computers never entered the home with the same emphasis; a metaphor for activities at home is much more difficult to find, as the level of involvement of personal preferences and emotional factors is dramatically higher.

In this context, a basic question for personal robotics should be asked, with regards to anthropomorphism: Can anthropomorphism be the right metaphor for introducing robots into human personal activities? Further, in the interaction with the personal robot, who is the master? The potential perception of an invasion of personal environment and personal activities, habits, and procedures can be a big barrier to acceptability.

In addition, there are ethological implications in the interaction with human users to be taken into account.42 The autonomous mobility of a humanoid can provoke instinctive reactions in a human, just as an animal of a different species can; thus, a period of unconscious analysis of the other’s behavior is needed before a positive attitude towards interaction can be generated. It is of the utmost importance that the robot shows movements and “expressions” that exclude aggressiveness.

A new interpretation of the concept of system autonomy is thus introduced in Figure 3: on the one hand, system autonomy may be highly desirable in the execution of unpleasant or repetitive tasks or in the case of an emergency for the user (for instance, in the case of a disabled user); on the other hand, the user may wish to be involved in tasks concerning their personal activities in their own environment. An experimental validation has been given in ref. 78, by comparing the execution of the same
task at different levels of system autonomy. Thus, human–robot interaction should be designed and implemented to optimize rather than minimize the level of user involvement. A possible solution is “modularity in autonomy,” in which different levels of use allow the user to decide when, how, and to what extent they will be involved in the execution of tasks. The definition of the boundary between system autonomy and system dependence (on the user’s control) is primarily driven by user preferences rather than by the technical limitations of the system.

When a machine must interact with a human user, safety issues are of first importance. This is particularly true in the case of personal robots. An open challenge in this framework is the combination of very basic safety devices with very fast recovery procedures.

Finally, the problem of cost affects the probability of success of a product. Robotics is intrinsically expensive, and proposing a robot in the family economy is much more difficult than introducing it in industrial contexts. Key factors for tackling the problem of cost are the concepts of modularity and integration. The recent mass diffusion of home automation technologies, and IT and telematic tools, is providing a fertile substrate for the introduction of a personal robot at home, not only from a technical point of view, but also due to the cost reduction that their wide diffusion is already causing.

The proposed approach to the development of personal robots is then based on the integration of anthropomorphic components for the replication of well-identified human capabilities, into an overall distributed system that cannot necessarily be based on a humanoid robotic module.

4. CASE STUDY: THE MOVAID ROBOTIC SYSTEM

The MOVAID system is a modular distributed robotic system for assistance to disabled and elderly people at home. It is composed of fixed workstations and a mobile robotic unit with navigation, manipulation, vision, and docking capabilities.

A multidisciplinary team (including engineers, industrial designers, anthropologists, medical doctors, and rehabilitation therapists) collaborated in the design and development of the system, taking a user-oriented approach to maximizing the acceptability of the system.

The analysis of user needs was based on interviews with potential end users (such as disabled people and their assistants and technicians and therapists), and involved 140 persons in Italy and Switzerland. Contact with end users clearly indicated a general negative attitude towards an autonomous machine in personal home activities; furthermore, the concept of a robot was often assimilated to science fiction humanoid robots, evoking fear and mistrust. The analysis of the users’ answers by psychological techniques led the designers to formulate the design prescriptions for MOVAID:

- for a close and positive interaction with the end user, the robotic assistant should have a friendly interface and be not only simple but also pleasant to use; in order to be truly integrated into everyday life, it should somehow be appealing not only in functionality and performance but even in accessibility; the level of user’s involvement should be optimized—avoided in repetitive or unpleasant tasks and fruitfully exploited in more pleasant tasks—by allowing the user to choose;
- in physical aspect, the system should be clearly artificial, avoiding the risk of evoking science fiction humanoid robots or, more generally, fake humans or monsters; caricature elements should be avoided as well, to avoid the perception of a toy or a pet robot; the look should be technological and scientific, to communicate efficiency and effectiveness, though a trade-off should be found between “high-tech” and “household”;
- the behavior of the system should communicate friendliness and confidence: easily understood, predictable, gentle movements; warnings before movements; no movements in the dark; standby in a reassuring “sleeping” position; approach to the user from below; and
• the user interface should involve the user, maximize activity, assist the user, and give pleasure.

Based on the results of the user need analysis, functional specifications were defined for the system. Six sample user profiles were synthesized, and three typical tasks identified, summarizing the system’s functionality.

In order to maximize the friendliness and appeal of the user interface, the layout was designed to be not so much computerlike, but rather TV-like (considering TV as one of the best-accepted technological devices at home). Thus, a large image coming from on-board cameras is shown to the user continuously, and the number of buttons is dynamically reduced to the minimum. The image on the screen is not only a means for the user to monitor what the robot is doing, but also a tool for human-robot interaction. In fact, it is possible for the user to collaborate with the robot by indicating objects and locations directly on the screen, via a point-and-click mechanism. Beyond matching user requirements, this solution also simplifies significantly some of the technical difficulties related to artificial perception.

The different levels of autonomy of the system were mapped onto four levels of use in the user interface. Such levels modulate the system autonomy from a “beginner” level, allowing the request of predefined tasks only, up to the “expert” level, including tele-operation. At intermediate levels (“standard” and “advanced”), the user is involved in the execution of tasks, at their convenience, and in error recovery.

According to the design prescriptions, the look of the mobile unit was designed to evoke appliances more than technological or medical devices, and to avoid anthropomorphism, by choosing rounded shapes and soft colors. Only the arm and hand have been kept anthropomorphic (using the Dexter Arm and Marcus Hand described in Section 2.2), for the following reasons:

• some anthropomorphic features (such as size, shape, and working space) better fit the application domain, that is, common activities at home; and
• anthropomorphic movements are more predictable, and therefore better accepted, and easier to program.

Details on the design of the MOVAID system can be found in refs. 35, 38, and 42.

4.1. The MOVAID System Architecture

As anticipated, the MOVAID system is composed of a mobile unit and fixed workstations. The mobile robotic unit can navigate in the house avoiding unexpected obstacles, can grasp and manipulate common objects, and can physically dock to the fixed workstations for data exchange and power supply. Physical docking allows a reduction in the complexity, size, and weight of the mobile unit, by reducing the battery pack (as only the capabilities to move from one fixed workstation to another is required) and the computing power (as only the low-level controllers are implemented on board) [31, 53].

The MOVAID mobile unit is composed of a four-wheeled mobile base supporting a robotic arm and hand. On the first link of the arm are mounted a pan-tilt head supporting two TV cameras and a laser-based self-localisation system. The mobile base is also equipped with a ring of ultrasound sensors for obstacle detection, and is partially covered by a tray for object transportation. An active bumper around the vehicle halts the system in the case of a collision. On the rear lower part of the mobile base the male docking system is mounted. The mobile unit structure is modular, so that the vehicle can be used on its own, as a mobile platform, and the arm can be mounted on a different support (a table or a wheelchair). Details on the MOVAID path planner, the arm controller, and the hand can be found in refs. 3, 20, and 97, respectively.

The mobile robotic unit can dock to a fixed workstation through a docking system composed of a special connector for transmission of power and data, and a two-d.o.f. mechanical support allowing connection even with low positioning accuracy. An Ethernet radio link allows bidirectional data flow between the fixed workstations and the mobile base when the robot is undocked. Through the radio link, the fixed workstations send commands to be executed by the mobile base, while the mobile base sends back the result of the command executed and the images acquired by the TV cameras. The hardware architecture of the mobile unit is composed of two PC-104 racks, connected through a serial link. The onboard resources are distributed onto the two racks.

The fixed workstations, which are standard personal computers, are located where main activities are carried out at home, such as the kitchen and the bedroom, and support the high-level control modules of the system. In the MOVAID demonstration scenario, two fixed workstations were used, one located in the bedroom (close to the possibly bedridden user), and one in the kitchen.
The fixed workstations allow access to the robot through a graphical human-machine interface, which can be used either by means of the standard PC mouse or by a specific human-machine interface, including M3S input devices. The input given by the user is processed by the proper software modules implemented on the fixed workstation, and is translated in the format required by the onboard low-level controllers.

According to acceptability concerns, different levels of autonomy have been designed for the MOVAID system. The user can choose if and to what extent they are involved in the execution of tasks, by interacting and collaborating with the robot. The implementation of the previously described concept of modularity in autonomy also has an impact on the design and implementation of the user interface and the system supervisor.

The Multimedia Man-Machine Interface (MMMI) allows the user to access the MOVAID system, providing tools for requiring tasks. Moreover, the MMI provides the user with information on system status. Different levels of use have been defined: the lowest level is characterised by high system autonomy and little or no involvement of the user during the execution of tasks. It is addressed to beginners, or to users that wish to be uninvolved in the execution of tasks (for instance, repetitive tasks). The higher the level, the lower the autonomy of the system and the more the involvement of the user, especially in object identification and error recovery.

The MMI also provides a continuous flow of visual data from the onboard cameras. Such information is useful in allowing the user to monitor robot behavior and, in particular, for allowing them to interact with the robot during the execution of tasks. The idea is that the user, seeing what the robot is seeing, could ask for tasks involving observed objects and could help the robot to identify objects by indicating them directly on the image. In the present configuration of the MOVAID demonstrator, the neural-based control schemes described in Sections 2.3 and 2.4 have not yet been implemented.

4.5. Validation of the MOVAID System with End Users

The MOVAID prototype was installed in a residential site for disabled people in Italy, where it was tested and evaluated by a few end users. The MOVAID system at work in the kitchen with a tetraplegic young man is shown in Figure 4.

The general aim of the validation of the MOVAID system was to survey the acceptability and perceived usability of the system, in terms of system efficiency, system effectiveness, interaction effectiveness, ease of use, ease of interaction, pleasure of use, helpfulness, robot behavior, robot aspect, pleasure of interaction, invasiveness, and system autonomy. Three different evaluation methods were used in the validation activity:

1. **functional evaluation**—evaluation of the technical performance of the system;
2. **usability evaluation**—evaluation of the user’s capability to interact with the system;
3. **indirect evaluation**—evaluation of the subjective, emotional, psychological implications deriving from the use of the system.

Data were collected using four tools:

1. **user profile forms**, collecting personal data on the users, as provided by themselves;
2. **user profile questionnaires**, answered by the users, collecting data on their current situation concerning personal assistance;
3. **evaluation forms**, collecting data on the evaluation of the performance of the system and of the effectiveness of the user–robot interaction, filled out by the operators (technicians and therapists)—these forms were used for the functional and usability evaluations;
4. **user questionnaires**, providing a subjective evaluation of the system by the user (indirect evaluation).
The robotic system was proposed to a sample of motor-disabled people, with different levels and typologies of disabilities. They were trained to use the MOVAID human-machine interface and to use specific aids for accessing the PC, when necessary. Then, they were asked to request a given task from the robot, at different levels of use of the interface. Validation trials were integrated with demonstrations of the system (through video and photographs), both in Italy and in other countries, involving a total of 64 people.

As a general result, the system was accepted very favorably in most cases, especially by severely motor-disabled users and those with poor or no functionality of upper limbs (whereas it was evaluated as a helpful but not strictly necessary tool by paraplegic people with full functionality of upper limbs). Some of the specific results of the validation trials are graphically reported in Figures 5–8. The visual feedback on the screen was confirmed as a comfortable feature for allowing the user to monitor the robot; the
point-and-click mechanism of interaction with the image was in general appreciated, and it did not introduce an additional burden on the user's activity.

The aesthetics of the system, though stimulating many comments and suggestions, seems to match the proposed goals of giving the system friendliness and an appliance-like appearance. The system was considered as acceptable in a domestic environment.

The difference in users' attitude between the first phase of analysis of users' needs and this phase of validation was clearly evident. In the first phase, users were proposed something which was almost completely unknown, and a generalized sense of mistrust emerged. In the phase of validation, however, users were asked to evaluate something much more concrete, which they could see while operating (live or in a video). This greatly changed the opinion of users who, in the validation phase, showed a much more positive attitude. Most users felt stimulated to propose new tasks, and many suggested modifications and improvements in relation to their own needs. The substantial change of opinions on a possible robotic assistant before and after the MOVAID experience is shown in Figure 9, and clearly demonstrates the viability of the adopted design methodology.
Can you see any advantages in using MOVAID?
Can you see any disadvantages in using it?
Do you think it could be useful?

Does the robot scare you when navigating?
Does the robot scare you when moving its arm?
Do you find the robot too noisy?
Do you find the robot too silent?

Figure 7. Validation results: Helpfulness.

Figure 8. Validation results: Robot behavior.
Can you imagine robotic assistance?

Don't know: 48%
Yes: 10%
No: 42%

Would you like to have a robotic assistant?

Don't know: 36%
No: 21%
Yes: 43%

Before MOVAID

After MOVAID

Figure 9. Attitudes towards a robotic personal assistant shown by a sample of motor-disabled persons, before and after the MOVAID project.

5. CONCLUSIONS

In this paper, we analyzed different approaches and technological implementations in the fields of humanoid and personal robotics. We proposed a general framework that identifies the objectives, synergies, and differences between humanoid and personal robots, with the support of extensive reference to previous and current work.

We presented our achievements in the design and implementation of anthropomorphic components and an integrated personal robot. This prototype was tested with real users, and the resulting qualitative and quantitative data on acceptability have been reported. This data could represent a very useful background for the identification of urgent and important research areas in the field.

Our conclusions are that there are tremendous technical challenges, and tremendous research and industrial opportunities for both humanoid and personal robotics. Though the two areas pose different challenges and applications, some of these are overlapping (e.g., development of anthropomorphic components and control techniques). Home applications certainly stand as a key application opportunity in the near future, thanks also to the massive development of mechatronics and telematics.

The challenge for humanoids is perhaps more technical, because it is inspired by the dream of replicating the intellectual and functional abilities of human beings. The development of a soccer team of humanoids capable of winning a match against a human soccer team has been proposed as a benchmark for humanoid robots, just as computers capable of winning a chess match against humans were considered a benchmark for artificial intelligence not many years ago.

The challenge of personal robotics is less technically defined, but at least as intriguing as the development of humanoids. In this field, design specifications are given by factors that are less familiar to robotics researchers, such as pleasure of interaction, acceptability, and usefulness. In the authors’ opinion, the real challenge for personal robotics is in the identification of the key functional specifications and the overall system configuration, including robotic modules, for obtaining final acceptability by the targeted end users.

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