The Evolution of Robotics Research

From Industrial Robotics to Field and Service Robotics

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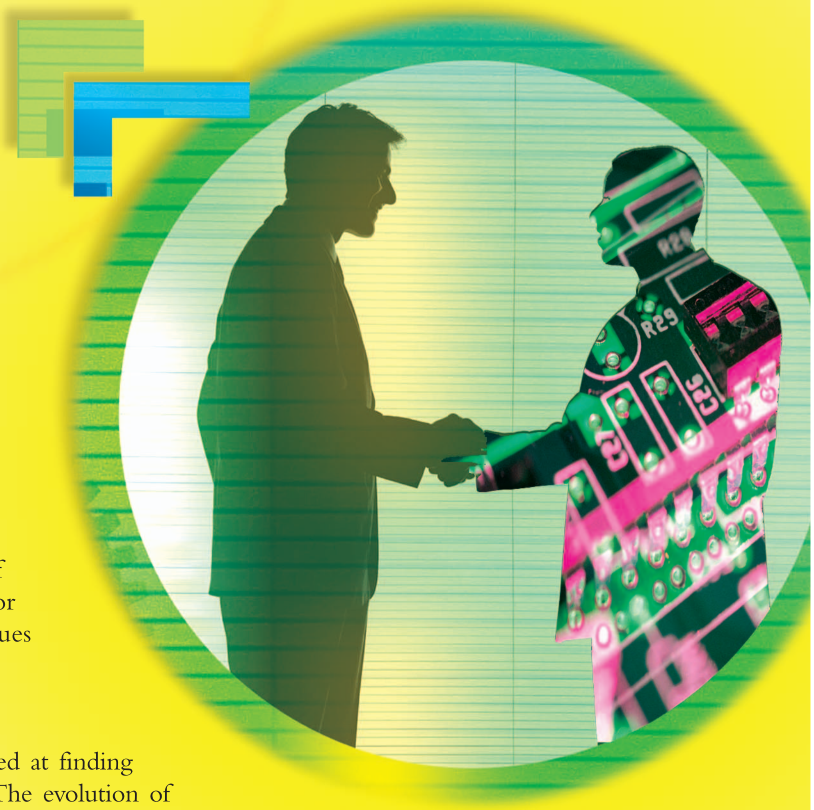
This article surveys the evolution of robotics research in the last half century as a response to the evolution of human social needs, from the industrial robotics that released the human operator from dangerous or risky tasks to the recent explosion of field and service robotics to assist the human. This article surveys traditional research topics in industrial robotics and mobile robotics and then expands on new trends in robotics research that focus more on the interaction between human and robot. The new trends in robotics research have been denominated service robotics because of their general goal of getting robots closer to human social needs, and this article surveys research on service robotics such as medical robotics, rehabilitation robotics, underwater robotics, field robotics, construction robotics and humanoid robotics. The aim of this article is to provide an overview of the evolution of research topics in robotics from classical motion control for industrial robots to modern intelligent control techniques and social learning paradigms, among other aspects.



Introduction

During the last 45 years, robotics research has been aimed at finding solutions to the technical necessities of applied robotics. The evolution of application fields and their sophistication have influenced research topics in the robotics community. This evolution has been dominated by human necessities. In the early 1960s, the industrial revolution put industrial robots in the factory to release the human operator from risky and harmful tasks. The later incorporation of industrial robots into other types of production processes added new requirements that called for more flexibility and intelligence in industrial robots. Currently, the creation of new needs and markets outside the traditional manufacturing robotic market (i.e., cleaning, demining, construction, shipbuilding, agriculture) and the aging world we live in is demanding field and service robots to attend to the new market and to human social needs.

This article is aimed at surveying the evolution of robotics and tracing out the most representative lines of research that are strongly related to real-world robotics applications. Consequently, many research topics have been omitted for

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one main reason: The authors' goal of tracking the evolution of research would not have been met by presenting a catalog of every research topic in such a broad area. Therefore these authors apologize to those authors whose research topic has not been reflected in this survey. The intention is not to imply that omitted topics are less relevant, but merely that they are less broadly applied in the real robotics world.

This article addresses the evolution of robotics research in three different areas: robot manipulators, mobile robots, and biologically inspired robots. Although these three areas share some research topics, they differ significantly in most research topics and in their application fields. For this reason, they have been treated separately in this survey. The section on robot manipulators includes research on industrial robots, medical robots and rehabilitation robots, and briefly surveys other service applications such as refueling, picking and palletizing. When surveying the research in mobile robots we consider terrestrial and underwater vehicles. Aerial vehicles are less widespread and for this reason have not been considered. Biologically inspired robots include mainly walking robots and humanoid robots; however, some other biologically inspired underwater systems are briefly mentioned. In spite of the differences between robot manipulators, mobile robots and biologically inspired robots, the three research areas converge in their current and future intended use: field and service robotics. With the modernization of the First World, new services are being demanded that are shifting how we think of robots from the industrial viewpoint to the social and personal viewpoint. Society demands new robots designed to assist and serve the human being, and this harks back to the first origins of the concept of the robot, as transmitted by science fiction since the early 1920s: the robot as a human servant (see Figure 1). Also, the creation of new needs and markets outside the traditional market of manufacturing robotics leads to a new concept of robot. A new sector is therefore arising from robotics, a sector with a great future giving service to the human being. Traditional industrial robots and mobile robots are being modified to address this new market. Research has evolved to find solutions to the technical necessities of each stage in the development of service robots.

Robot Manipulators

A robot manipulator, also known as a robot arm, is a serial chain of rigid limbs designed to perform a task with its end-effector. Early designs concentrated on industrial manipulators, to perform tasks such as welding, painting, and palletizing. The evolution of the technical necessities of society and the technological advances achieved have helped the strong growth of new applications in recent years, such as surgery assistance, rehabilitation, automatic refuelling, etc. This section surveys those areas that have received a special, concentrated research effort, namely, industrial robots, medical robots, and rehabilitation robots.

Industrial Robots

It was around 1960 when industrial robots were first introduced in the production process, and until the 1990s industrial robots dominated robotics research. In the beginning, the automotive industry dictated the specifications industrial robots had to meet, mainly due to the industry's market clout and clear technical necessities. These necessities determined which areas of investigation were predominant during that period.

One such area was kinematic calibration, which is a necessary process due to the inaccuracy of kinematic models based on manufacturing parameters. The calibration process is carried out in four stages. The first stage is mathematical modeling, where the Denavit-Hartenberg (DH) method and the product-of-exponential (POE) formulation lead the large family of methods. A detailed discussion of the fundamentals of kinematic modeling can be found in the literature [1]. The gap between the theoretical model and the real model is found in the second stage by direct measurement through sensors. Thus, the true position of the robot's end effector is determined, and by means of optimization techniques, the parameters that vary from their nominal values are identified in the third stage. Last, implementation in the robot is the process of incorporating the improved kinematic model. This process will depend on the complexity of the machine, and iterative methods will have to be employed in the most complex cases. Research in robot calibration remains an open issue, and new methods that reduce the computational complexity of the calibration process are still being proposed [2], [3].

Another important research topic is motion planning, wherein subgoals are calculated to control the completion of the robot's task. In the literature there are two types of algorithms, implicit methods and explicit methods. Implicit methods specify the desired dynamic behavior of the robot. One implicit scheme that is attractive from the computational point of view is the potential field algorithm [4]. One disadvantage of this approach is that local minima of the potential field function can trap the robot far from its goal. Explicit methods provide the trajectory of the robot between the initial and final goal. Discrete explicit methods focus on finding discrete

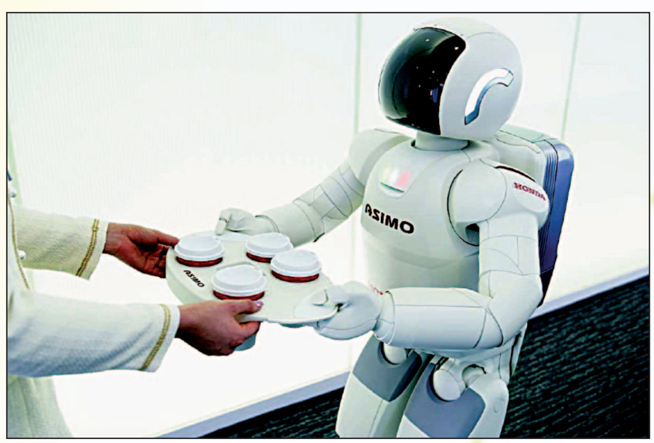


Figure 1. *ASIMO. Photograph courtesy of American Honda Motor Co.*

collision-free configurations between the start and goal configurations. These methods consist mainly of two classes of algorithms, the family of road-map methods that include the visibility graph, the Voronoi diagram, the free-way method and the Roadmap algorithm [5], and the cell-decomposition methods [6]. Continuous explicit methods, on the other hand, consist in basically open-loop control laws. One important family of methods is based on optimal-control strategies [7], whose main disadvantages are their computational cost and dependence on the accuracy of the robot's dynamic model.

Besides planning robot motion, control laws that assure the execution of the plan are required in order to accomplish the robot's task. Thus, one fundamental research topic focuses on control techniques. A robot manipulator is a nonlinear, multi-variable system and a wide spectrum of control techniques can be experimented here, ranging from the simpler proportional derivative (PD) and proportional integral derivative (PID) control to the computed-torque method [8], and the more sophisticated adaptive control [9] whose details are out of the scope of this survey.

Typical industrial robots are designed to manipulate objects and interact with their environment, mainly during tasks such as polishing, milling, assembling, etc. In the control of the interaction between manipulator and environment, the contact force at the manipulator's end effector is regulated. There are diverse schemes of active force control, such as stiffness control, compliant control, impedance control, explicit force control and hybrid force/position control. The first three schemes belong to the category of indirect force control, which achieves force control via motion control, while the last two methods perform direct force control by means of explicit closure of the force-feedback loop. Readers who wish to study this subject in detail will find an interesting account in [10].

An attractive alternative for implementing force-control laws is the use of passive mechanical devices so that the trajectory of the robot is modified by interaction forces due to the robot's own accomodation. An important example of passive force control is the remote center of compliance (RCC) system patented by Watson in 1978 [11] for peg-in-hole assembly. Passive force control is simpler than active force control laws but has disadvantages, such as lacking flexibility and being unable to avoid the appearance of high contact forces.

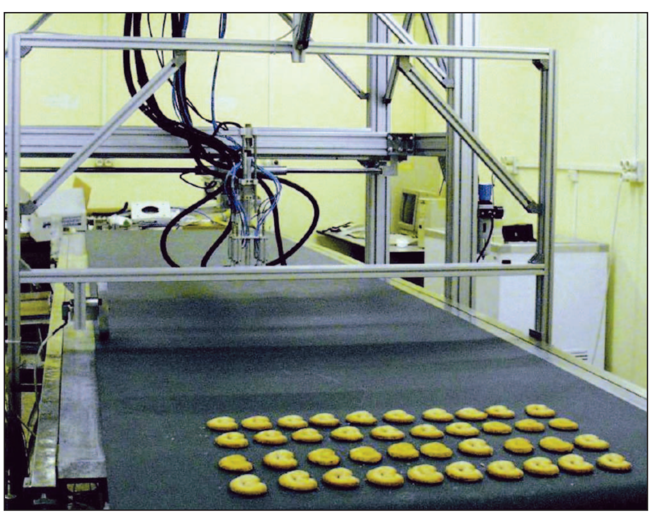


Figure 2. *Robots in the food industry.*

As 1990 began, new application areas for industrial robots arose that imposed new specifications, with flexibility as the principal characteristic. The new industries that introduced industrial robots in their productive process were the food and pharmacy industries (see Figure 2). Postal services too looked for robotic systems to automate their logistics. The main requirement was the capacity to accommodate variations in product, size, shape, rigidity (in the case of foods), etc. The ability to self-adapt to the product and the environment became the issue in the following lines of investigation in the area of industrial robotics. The main line of research now is aimed at equipping the control system with sufficient intelligence and problem-solving capability. This is obtained by resorting to artificial-intelligence techniques. Different artificial intelligence (AI) techniques are used to provide the robot with intelligence and flexibility so it can operate in dynamic environments and in the presence of uncertainty. Those techniques belong to three areas of artificial intelligence: learning, reasoning and problem solving [12]. Among the diverse learning algorithms, inductive learning is the most widely used in robotics, in which the robot learns from preselected examples [13]. Typical reasoning paradigms in robotics include fuzzy reasoning [14], mostly used in planning under uncertainty, spatial reasoning, and temporal reasoning. The techniques most commonly used in robotics for problem solving are means-end reasoning, heuristic searching, and the blackboard (BB) model.

Another solution to the control of robots in dynamic or unknown environments consists of introducing the operator in the control loop, such that the robot is remotely operated. The success of a teleoperation system relies on the correct feedback of the robot interaction with the environment, which can be visual, tactile or force reflection. The greatest disadvantage that teleoperated systems involve are transmission delays when the distance between the operator and the robot is significant, like in space teleoperation or over the Internet. Some research has explored solutions to this problem, such as interposing a virtual robot in charge of environment feedback, but this procedure is only valid if the robot works in structured environments. Another solution is teleprogramming, in which the operator sends high-level commands and the robot carries out the task in closed-loop control. Recently, considerable attention has been devoted to Internet-based teleoperation, in which the transmission delay is variable. For direct force feedback, wave-variable-based approaches have been used extensively, and they have been further extended to include estimation and prediction of the delay. A comprehensive survey can be found in [15].

With the rapid modernization of the First World, new types of services are being required to maintain a certain quality of life. A new, promising robotics sector is arising to serve the human being. Traditional industrial robots are being modified to respond to this new market, yielding surgery robots, refueling robots, picking and palletising robots, feeding robots, rehabilitation robots, etc. Two of the most relevant service applications of robot manipulators are in the field of medical robots and rehabilitation robots that are catching the interest of researchers all over the world. In the following subsections, we will summarize research topics in medical robotics and rehabilitation robotics.

The new trends in robotics research have been denominated service robotics because of their general goal of getting robots closer to human social needs.

Medical Robots

In recent years, the field of medicine has been also invaded by robots, not to replace qualified personnel such as doctors and nurses, but to assist them in routine work and precision tasks. Medical robotics is a promising field that really took off in the 1990s. Since then, a wide variety of medical applications have emerged: laboratory robots, telesurgery, surgical training, remote surgery, telemedicine and teleconsultation, rehabilitation, help for the deaf and the blind, and hospital robots. Medical robots assist in operations on heart-attack victims and make possible the millimeter-fine adjustment of prostheses. There are, however, many challenges in the widespread implementation of robotics in the medical field, mainly due to issues such as safety, precision, cost and reluctance to accept this technology.

Medical robots may be classified in many ways: by manipulator design (e.g., kinematics, actuation); by level of autonomy (e.g., preprogrammed versus teleoperation versus constrained cooperative control); by targeted anatomy or technique (e.g., cardiac, intravascular, percutaneous, laparoscopic, micro-surgical); by intended operating environment [e.g., in-scanner, conventional operating room (OR)], etc. Research remains open in the field of surgical robotics, where extensive effort has been invested and results are impressive. Some of the key technical barriers include safety [16], where some of the basic principles at issue are redundancy, avoiding unnecessary speed or power in actuators, rigorous design analysis and multiple emergency stop and checkpoint/restart facilities. Medical human-machine interfaces are another key issue that draws upon essentially the same technologies as other application domains. Surgeons rely on vision as their dominant source of feedback; however, due to the limited resolution of current-generation video cameras, there is interest in optical overlay methods, in which graphic information is superimposed on the surgeon's field of view to improve the information provided [17]. As surgeons frequently have their hands busy, there has been also interest in using voice as an interface. Force and haptic feedback is another powerful interface for telesurgery applications [18]. Much of the past and present work on telesurgery involves the use of master-slave manipulator systems [19], [20]. These systems have the ability to feed forces back to the surgeon through the master manipulator, although slaves' limitations in sensing tool-to-tissue forces can somewhat reduce this ability.

The field of medical robotics is expanding rapidly and results are impressive as a large number of commercial devices are being used in hospitals. However, societal barriers have to be overcome and significant engineering research effort is required before medical robots have widespread impact on health care.

Rehabilitation Robots

Activity in the field of rehabilitation robotics began in the 1960s [21] and has slowly evolved through the years to a point where the first commercially successful products are now available. Today, the concept of "rehabilitation robot" may include a wide array of mechatronic devices ranging from artificial limbs to robots for supporting rehabilitation therapy or for providing personal assistance in hospital and residential sites. Examples include robots for neuro-rehabilitation [22], power-augmentation orthosis [23], rehabilitative orthosis, etc. The field of rehabilitation robotics is less developed than that of industrial robotics. Many assistive robotic systems have featured an industrial robot arm for reasons of economy and availability [24]. However, the specifications for robots in these two application areas are very different. The differences arise from the involvement of the user in rehabilitation applications. Industrial robots are typically powerful and rigid to provide speed and accuracy. They operate autonomously and, for reasons of safety, no human interaction is permitted. Rehabilitation robots must operate more slowly and be more compliant to facilitate safe user interaction. Thus, rehabilitation robotics is more akin to service robotics, which integrates humans and robots in the same task. It requires safety and special attention must be paid to human-machine interfaces that have to be adapted for disabled or nonskilled people operating a specific programming device. It is also recognized that there is a need for research and development in robotics to focus on developing more flexible systems for use in unstructured environments. The leading developments of this type in rehabilitation robotics concern, among other topics, mechanical design (including mobility and end-effectors), programming, control and man machine interfaces [25]. Subsection "Humanoid Robots" of this article expands on new research into human-robot interaction.

Mobile Robots

The term mobile robot describes a robotic system able to carry out tasks in different places and consisting of a platform moved by locomotive elements. The choice of the locomotive system depends firstly on the environment in which the robot will operate. This can be aerial, aquatic or terrestrial

Another solution to the control of robots in dynamic environments consists of introducing the operator in the control loop.

(see Figure 3). In the aquatic and aerial environments, the locomotive systems are usually propellers or screws, although at the seabed legs are also used. The choice of the locomotive system on earth is more complicated due to the variety of terrestrial environments. Wheels, tracks, and legs are typical terrestrial locomotive elements.

Mobility provides robots with enhanced operating capacity and opens up new areas of investigation. Some such areas are common to all mobile robots, like the navigation problem, whereas others deal more specifically with a certain locomotion system, like the walking gait.

Practically by the time industrial robots were introduced in the production process, mobile robots were installed in the factory. This was around 1968, and the robots were mainly automated guided vehicles (AGVs), vehicles transporting tools and following a predefined trajectory. Nevertheless, the research in this area deals now with autonomous indoor and outdoor navigation. Autonomous mobile-robot navigation consists of four stages: perception of the environment, self-localization, motion planning and motion generation.

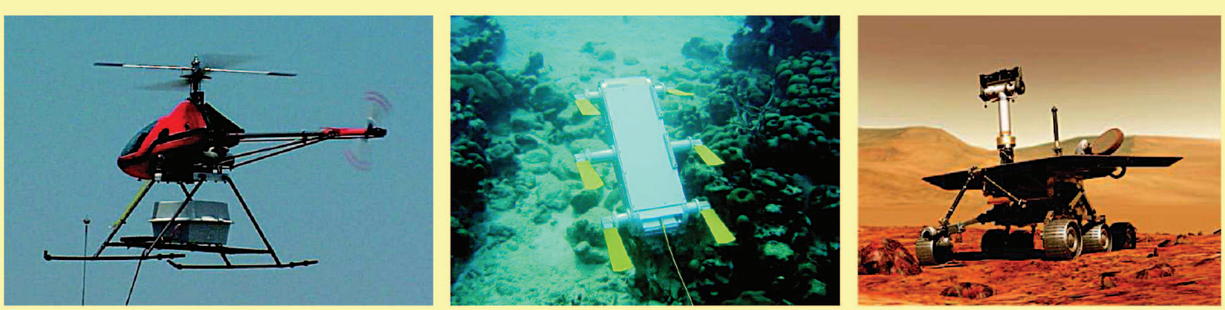
In structured environments, the perception process allows maps or models of the world to be generated that are used for robot localization and motion planning. In unstructured or dynamic environments, however, the robot has to learn how to navigate. Navigation is, therefore, one of the main applications of artificial intelligence to robotics, where learning, reasoning and problem solving come together. The main research in mobile robotics is focusing on robot localization and map generation.

Robot Localization

The localization process allows a mobile robot to know where it is at any moment relative to its environment. For this purpose sensors are used that enable measurements to be taken related to the robot's state and its environment. These sensors accumulate errors and provide noisy measurements. For that reason, a great deal of research centers on improving position estimation by means of integrating measurements taken by several sensor types using Kalman filter techniques. Localization can be local or global. The simplest solution is local localization, where the robot incrementally corrects its position relative to an initial location, whereas in global localization the robot's initial position is not needed. In addition, the location process can be based on the sensorial identification of landmarks in the environment whose location is well known, or it can be based on maps or models of the environment and identify characteristic elements of the mapped environment. In this latter case, probabilistic approaches are used to solve the problem of uncertainty in the sensorial information.

Localization algorithms in the literature all come from the Bayes filter, a recursive equation that allows the robot's pose to be estimated from the perceptual model and the motion model. The problem is that implementing the Bayes filter is computationally inefficient and the possible simplifications lead to diverse localization algorithms. A classification is shown in Figure 4. There are two major families of algorithms, differing in how they represent the robot's belief. Where the robot's belief is modeled by means of multivariate Gaussian densities, we find the methods based on the Kalman Filter, whereas if we use multimodal distributions, we find Markov localization. The unimodal representation of the robot's belief is valid only for local localization, and Kalman-filter-based techniques have proven to be robust for keeping track of the robot's position [26].

Within the family of Markov localization, methods differ on the type of discretization that is used for the representation of the state space. This can be based on the topological structure of the environment; however, these methods are only valid for landmark-based localization, due to their low resolution [27]. To deal with multimodal-probability densities at a fine resolution, the significant part of the state space can be discretized and used for an approximation of the robot's belief, e.g., by means of a piece-wise constant function. These



(a) (b) (c)

Figure 3. *Mobile robots in various environments. (a) VAMPIRA (Photograph courtesy of DISAM-UPM). (b) Aqua (Photograph courtesy of McGill University). (c) Mars Exploration Rover (Photograph courtesy of NASA/JPL-Caltech).*

methods, known as grid-based Markov localization, are powerful tools for global localization, but they are computationally expensive [28]. Finally, the robot's belief can be represented by a set of weighted random samples (or particles) of robot positions and constrained based on observed variables. Fast sampling and its ability to represent arbitrary densities enables global localization to be performed efficiently. This gives rise to the Monte Carlo and condensation methods, generically known as particle filters. A discussion of their properties can be found in [29].

Robotic Mapping

Because map-based robot localization and robotic mapping are interdependent, research since 1990 has focused on solving both problems simultaneously. However, before then, the field of mapping was divided into metric and topological approaches. Metric maps capture the geometric properties of the environment [30], while topological maps describe the connectivity of different places by means of nodes-and-arcs graphs [31]. In practice, metric maps are finer grained than topological maps, but higher resolution comes at a computational burden. Metric maps can be discretized based on the probability of space occupation. The resulting mapping approaches are known as occupancy-grid mapping [32]. In contrast, the metric maps of geometric elements retain positions and properties of objects with specific geometric features [33].

Since 1990, robotic mapping has commonly been referred to as simultaneous localization and mapping (SLAM). Some methods are incremental and allow real-time implementation, whereas others require several passes through the whole of the perceived data. A broad family of incremental methods employ Kalman filters to estimate the map and the robot location and generate maps that describe the position of landmarks, beacons or certain objects in the environment [34]–[36]. Extensions of the algorithms based on the Kalman filter include the FastSLAM [37], the Lu/Milios algorithm [38] and very recently, the sparse extended information filter [39], based on the inverse of the extended Kalman filter (EKF). An alternative family of methods is based on Dempster's Expectation Maximization algorithm, which tries to find the most probable map by means of a recursive algorithm [40]. These approaches solve the correspondence problem between sensorial measurement and objects in the real world.

Recently researchers have been working on mapping dynamic environments. This is a considerable problem, since many realistic applications for robots are in non-static environments. Although Kalman-filter methods can be adapted for mapping dynamic environments by supposing landmarks that move slowly over time, and, similarly, occupancy-grid maps may consider some motion by reducing the occupancy over time, map generation in dynamic environments has been poorly explored. There are a few algorithms based on the dynamism of the environment [41], [42]. Many questions, however, remain open, such as how to differentiate between the static and dynamic parts of the environment and how to represent such information on the map. A complete survey of mapping methods can be found in [43].

Mobile robots are traveling from laboratory prototypes to real-world applications. Direct service applications of mobile robots include cleaning and housekeeping, where autonomous vacuum cleaners and lawn mowers take advantage of all the research in mobile navigation to help at home. Mobile robots also show potential for use as tour guides at museums and as assistants in offices, hospitals and other public venues. Such robots address key problems of intelligent navigation, such as navigation in dynamic environments, navigation in unmodified environments, short-term human-robot interaction and virtual telepresence [44]. Surveillance is another potential application of mobile-robot technology and private security companies are becoming interested in incorporating guard robots.

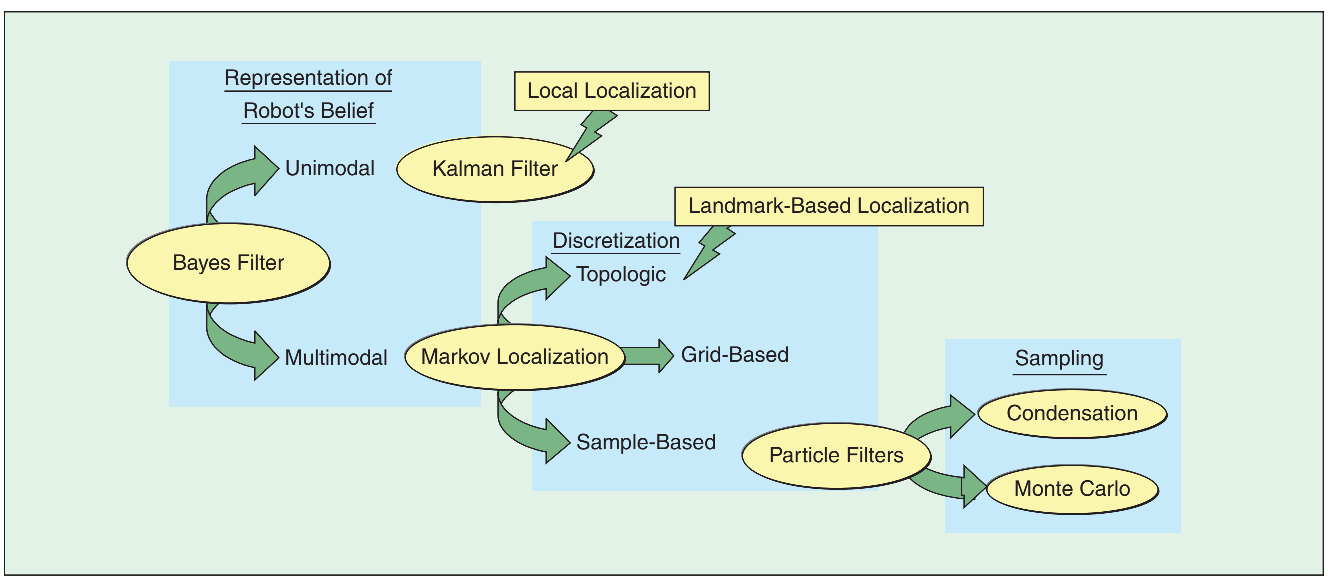


Figure 4. A classification of localization algorithms.

With the rapid modernization of the First World, new types of services are being required to maintain a certain quality of life.

Underwater Robots

More than 70% of the earth is covered by ocean. However, little effort has been made to utilize or protect this vast resource, compared to space or terrestrial programs.

During the last few years, the use of underwater robotic vehicles has rapidly increased, since such vehicles can be operated in the deeper, riskier areas that divers cannot reach. The potential applications of such vehicles include fishing, underwater pollution monitoring, rescue, and waste cleaning and handling in the ocean as well as at nuclear sites. Most commercial unmanned underwater robots are tethered and remotely operated; they are as a group, referred to as remotely operated vehicles (ROVs). However, extensive use of manned submersibles and ROVs is currently limited to a few applications because of very high operational costs, operator fatigue and safety issues. The demand for advanced underwater robot technologies is growing and will eventually lead to specialized, reliable, fully autonomous underwater vehicles (AUVs). In recent years, various research efforts have increased vehicle autonomy and minimized the need for the presence of human operators. A self-contained, intelligent, decision-making AUV is the goal of current research in underwater robotics. AUVs offer a challenging field for investigation into motion planning and control problems for robots operating in unstructured environments with limited on-line communication. Artificial-intelligence techniques have been used to introduce some intelligence and to enable the vehicle to react to unexpected situations. Also, providing the control system with both motion- and force-control capabilities becomes crucial for the successful execution of complex missions. Other areas of challenging research include the avoidance of significant external disturbances, sensing and localization methods that have to deal with noisy and dark environments and the impossibility of electromagnetic transmission. Interested readers can find a nice survey on AUV research topics such as dynamics, control systems, navigation and sensors, communications, power systems, pressure hulls and fairing and mechanical manipulators in [45].

Some researchers believe that one day autonomous vehicles will use the efficient mechanics of fish propulsion for scientific research at sea. Biological inspiration is thus reaching underwater-robot design. Although the aim of general research into fish robots is to understand the complex fluid mechanics that fishes use to propel themselves, in the near future, using fish-like propelling methods for autonomous vehicles could have enormous energy savings and increase the amount of time a machine could swim [46]. There is also some very active biologically-inspired research going on in legged underwater robots [47], [48].

Biologically Inspired Robots

Apart from traditional mobile vehicles that use wheels and tracks as locomotion systems, there is widespread activity in introducing inspiration from biology to produce novel types of robots with adaptive locomotion systems. Probably the most widely used biologically inspired locomotion system is the leg. However, there are some research groups focusing on other types of locomotion, such as the systems used by snakes and fishes. Our survey here will focus on walking robots and humanoid robots because of their more extended use. Both walking robots and humanoids use legs as their locomotion systems; however they differ in their research topics and service applications. Moreover, research on humanoid robotics does not only involve all aspects related to locomotion, but includes research on other "human" aspects as well, such as communication, emotion expression and so on. For this reason, we survey them separately.

Walking Robots

There has been great effort in studying mobile robots that use legs as their locomotion system. Some developments are shown in Figure 5. The legs of walking robots are based on two- or three-degrees-of-freedom (DOF) manipulators, and therefore walking robots share some of the technical problems typical of both industrial robots and mobile robots.

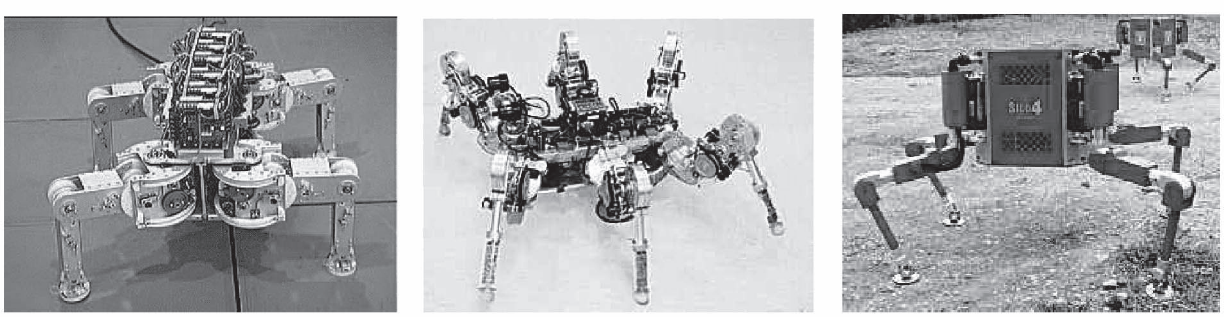


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Figure 5. *(a) Titan-VIII (Photograph courtesy of Tokyo Institute of Technology). (b) Lauron III (Photograph courtesy of FZI Forschungszentrum Informatik). (c) SILO4 (Industrial Automation Institute—CSIC).*

Movement on legs confers walking robots certain advantages as opposed to other mobile robots.

- Legged robots can negotiate irregular terrain while maintaining their body always leveled without jeopardizing their stability.
- Legged robots boast mobility on stairs, over obstacles and over ditches as one of their main advantages.
- Legged robots can walk over loose and sandy terrain.
- Legged robots have inherent omnidirectionality.
- Legged robots inflict much less environmental damage than robots that move on wheels or tracks.

However, at the same time, legs pose a number of problems of their own. Indeed, legged-robot research focuses on everything related to leg motion and coordination during robot navigation.

Robot stability is a related research topic. Roughly speaking, a walking robot is stable if it is able to keep its balance. Research on walking-robot stability began in 1968, when McGhee and Frank first defined the static stability of an ideal walking robot [49]. The idea of static stability was inspired by insects and assumed the absence of inertia in the motion of the robot limbs. However, during the motion of the usually heavy limbs and body of a robot, some inertial effects and other dynamic components (friction, elasticity, etc.) were found to arise, restricting robot movements to low, constant velocities. Thus, the adoption of static stability limited walking robots' speed of motion, and subsequently, researchers started to think about dynamic stability, where robot dynamics come into play. A complete survey on walking-robot stability margins and a qualitative classification can be found in [50].

Research into robot stability is highly related to another research topic, walking gait. The leg is a locomotion element that is not continuously in contact with the ground. For this reason it is important to determine the sequence of leg and body movements and also the footholds, to mantain stability. Thus, as Figure 6 shows, depending on the type of stability criterion used, there are two types of gaits, statically stable gaits and dynamically stable gaits. Statically stable gaits come from pre-90s research in walking robots. They have the characteristic of simplifying the control of robots with heavy limbs. Statically stable gaits can be classified into periodic and aperiodic. Periodic gaits consist in a predefined sequence of movements that are repeated cyclically [49], [50] whereas aperiodic gaits result from some type of online reasoning [50], [51]. Aperiodic gaits are more flexible for negotiating uneven terrain. In order to take advantage of the above mentioned walking-robot features and to compete with wheeled or tracked vehicles, legged robots need to be faster, so they need dynamically stable gaits. Research on dynamic gaits arose in the early 1990s. The dynamically stable gaits studied so far have been inspired by nature. Although nine different gaits have been distinguished for quadruped animals (walk, amble, trot, pace, canter, transverse gallop, rotary gallop, bound, and pronk) [52], the dynamic gaits developed for walking machines are basically limited to the trot, the pace and the bound. Most earlier studies on dynamic gaits employed precise models of a robot and an environment and involved planning joint trajectories as well as controlling joint motions on the basis of an analysis of the models [53], [54]. However, for a legged robot to walk or run dynamically on a variety of irregular terrains, this kind of approach is not effective. Based on biological studies, a few robotics researchers have attempted to solve the problem of dynamic walking and running in legged robots using neural oscillators. Nevertheless, very few have succeeded in using real robots on various irregular terrains [55].

Legs confer walking robots certain advantages as opposed to other mobile robots.

The biological inspiration for the design and development of legged robots has led to the thought that one day walking robots will replace wheeled machines on natural uneven terrain, yet there are still virtually no real walking robots robust enough to walk successfully in natural environments. In spite of initial expectations, most walking robots are still laboratory prototypes, and their application in the

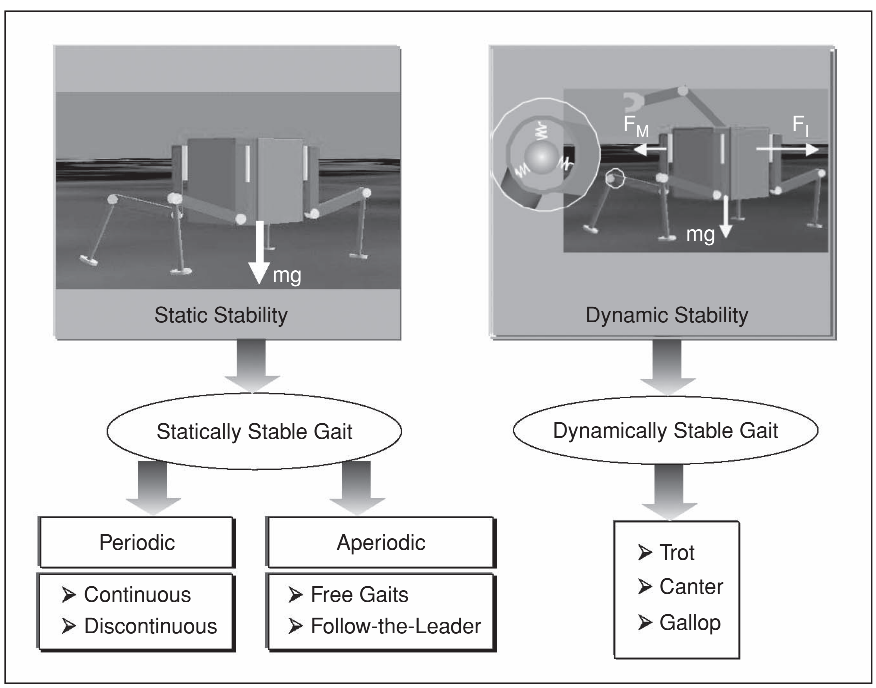
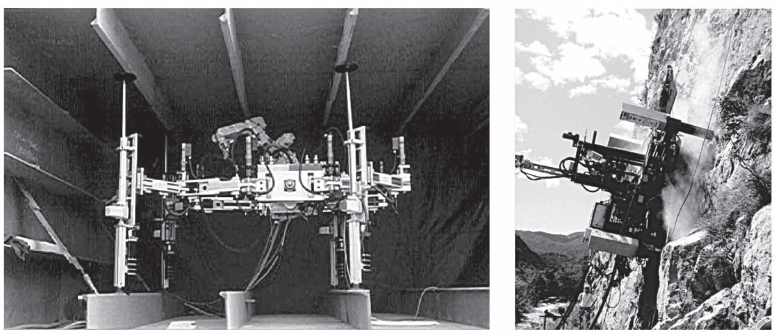


Figure 6. *Types of stability criteria and gaits for walking robots.*

real world is still far from occurring. Research on the adaptation of walking robots to environmental perturbations, which is a problem of paramount importance if legged robots are to be introduced into industrial, field and service processes, is very hard to solve and most researchers prefer to move to other emerging fields where innovation is easier just because the field is newer and simulation is a perfect tool for theorizing. Only a few researchers insist on solving real problems. In spite of these difficulties, there are some emerging applications of walking robots in field and service processes. The idea of using legged machines for humanitarian assistance for demining has been under development for about the last ten years, and some prototypes have already been tested [56]–[58].

Another field application of walking robots is in agriculture and forestry. Environmental considerations are playing an increasingly important role in forestry. Agricultural and forestry robots usually use wheels or tracks as their locomotion system. If they drive over an agricultural field or forest floor, they can cause considerable damage to the land.

Walking machines can play a relevant role in the future, cleaning, inspecting and maintaining buildings and other structures. Their advantages over other kinds of vehicles arise from the fact that in construction environments there is no prepared motion surface. Vehicles can only operate if various kinds of legs or arms exist which can support the actions of navigation and task performance. Welding automation in ship building [59] and consolidation of rocky walls and slopes by drilling [60] are two examples of this progress (see Figure 7).



(a) (b)

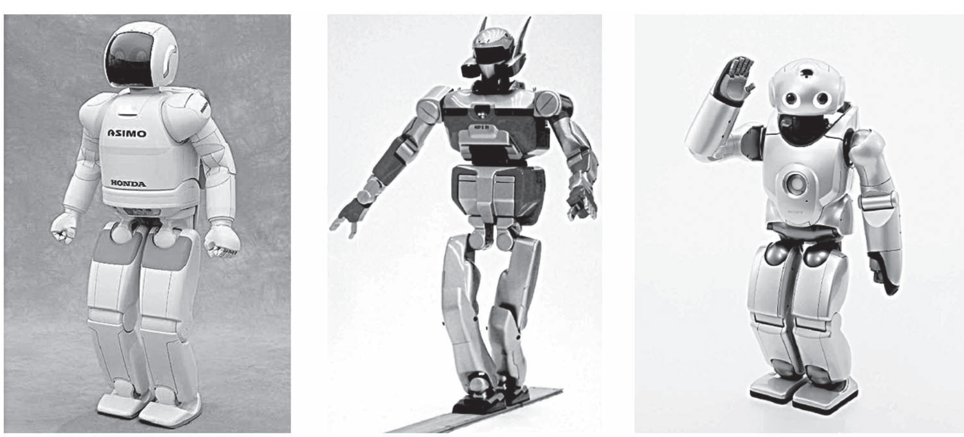
Figure 7. Walking robots in construction industry. (a) ROWER, a walking platform for ship building, Industrial Automation Institute—CSIC. (b) Roboclimber, a 3500kg four legged robot designed to work remotely on rocky sloped mountains, a joint project by ICOP Spa., Space Applications Services (SAS), Otto Natter Prazisionenmechanik GmbH, Comacchio SRL, Te.Ve. Sas di Zannini Roberto & Co. (TEVE), MACLYSA, D'Appolonia Spa., University of Genova-PMAR Laboratory, and Industrial Automation Institute—CSIC.

Humanoid Robots

When talking about dynamically stable walking robots, humanoid robots come to mind. Actual autonomous biped robots did not appear until 1967, when Vukobratovic *et al.* lead the first experiments with dermato-skeletons. The first controller-based biped robot was developed at Waseda University, Tokyo, Japan, in 1972. The robot was called WL-5.

Although the first bipeds were highly simplified machines under statically stable control, later developments have yielded truly sophisticated, extremely light, skillful robots (see Figure 8). These novel developments have fed a huge amount of research that can be grouped into three major research areas: gait generation, stability control, and robot design.

There are two types of approaches in gait generation for humanoids. The first type of approach consists in generating a gait off-line [61]. This method, however, cannot cope with adaptation to changing environments. The second type of method is an improvement that generates a proper gait periodically and determines the desired angles of every joint on-line [62]. There has also been some effort put into reducing power consumption during the walking gait [63].



(a) (b) (c)

Figure 8. Latest biped robots. Photograph of ASIMO courtesy of American Honda Motor Co. Photograph of HRP-2 courtesy of Kawada Industries, Inc. Photograph of QRIO courtesy of Sony Entertainment Robot Europe.

In robot-stability control, the zero moment point (ZMP) stability criterion is broadly used. The ZMP is the point on the support plane where the resultant of ground-reaction forces is applied [64]. The biped robot is considered dynamically stable if the ZMP lies inside the supporting area. Most authors try to control robot stability by controlling the ZMP [65]. Due to the complexity of computing a dynamic model, some authors prefer to control robot stability by tracking the pseudo-ZMP by means of assuming an ideal system [66]. The pseudo-ZMP position is computed as the projection of the robot's center of mass, which only needs to consider robot kinematics. There is also a great deal of ongoing research on enhancing stability with ankle-joint and waist-joint motions [67] and on measuring and compensating for the ZMP [68]. Some difficulty appears in the ZMP computation during the double support phase when the two feet are lying on two different surfaces. Indeed, the concept of ZMP is intrinsically related to walking on a single plane surface. To solve this problem, the notions of virtual equivalent surface and pseudo-ZMP have been proposed [69]. Note that this concept of pseudo-ZMP does not coincide with the above-mentioned pseudo-ZMP that only considers robot kinematics. Although its authors named it "pseudo-ZMP," in order to avoid confusion the term "virtual-ZMP" could be used instead to refer to the computation of the ZMP on irregular ground.

The third research topic in biped robots attempts to achieve better robot designs that improve robot stability and motion. The design aspects it focuses on mostly involve actuators, such as dc motors [70], artificial muscles [71] and other special actuators that guarantee power efficiency [72]. Robots for uneven terrains or other specific fields have also been proposed [73].

Research in humanoid robotics is currently shifting from locomotion issues to interaction between humans and robots. The dexterity of Asimo, Qrio, and HRP-2 for moving up and down stairs, sitting down and standing up and dancing is making it difficult for biped-locomotion researchers to keep at the summit of legged-robotics research. New trends in humanoid-robotics research consider the robot's ability to interact with humans safely and the robot's ability to express emotions. The final goal will be to insert humanoid robots into the human environment, to assist the elderly and the disabled, to entertain children and to communicate in a natural language. Research topics include the following.

1) Friendly human-robot interfaces that make it easier for non-skilled users to operate a robot. Speech-recognition systems [74], electromyogram [75], and electrooculogram [76] signal interpretation are some of the approaches being considered.
2) Safe human-robot interaction. The problem is being overcome by considering both safe actuation control designs that reduce the impact loads associated with uncontrolled motion [77] and safe robot-motion planning [78].
3) Emotion expression and perception. The exciting research in this direction is envisaged for applications such as personal and social robots [79], [80].

Research in humanoid robotics is currently shifting from locomotion issues to interaction between humans and robots.

4) Social learning. New learning approaches are being envisaged in a human-like way. In contrast to statistical learning approaches, the new learning approaches help robots quickly learn new skills and tasks from natural human instruction and few demonstrations. Socially guided learning includes learning by imitation [81] and learning by tutelage [82].

Research dealing with biped locomotion remains open in the area of dynamic stability in walking while manipulating objects and contacting the environment [83], [84].

Biped locomotion is also inspiring new research in exoskeletons, that is, human-performance augmentation systems featuring self-powered, controllable, wearable exoskeletal devices and/or machines (see Figure 9). The overall goal of this challenging research area is to develop devices and machines that will increase the speed, strength and endurance of people. The military application for soldiers in combat environments is clear. However, the very first

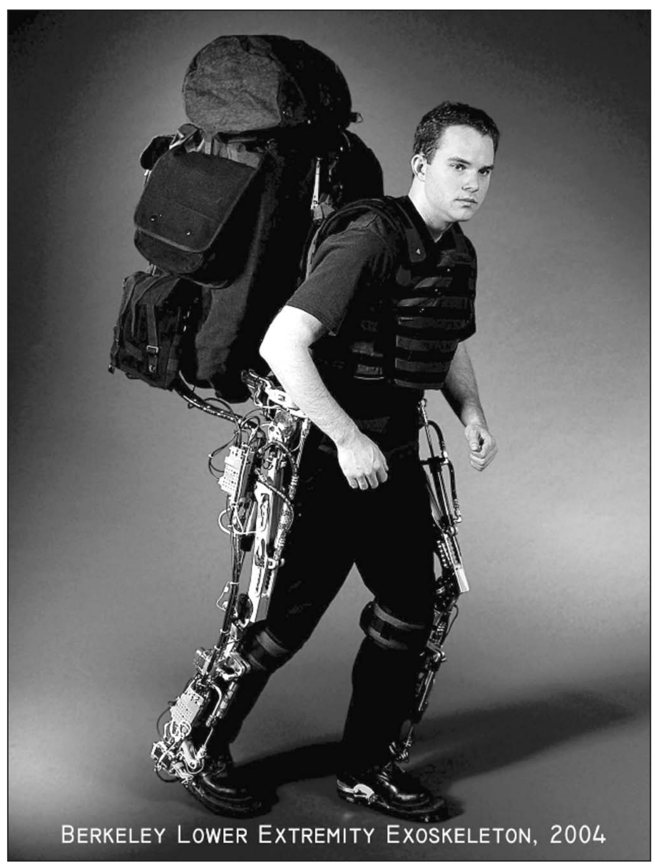


Figure 9. *Berkeley exoskeleton (BLEEX). Photograph courtesy of Prof. Kazerooni.*

commercially available exoskeleton, called HAL-5, is designed to help elderly and disabled people walk, climb stairs and carry things around. HAL-5, from the University of Tsukuba/CYBERDYNE, Inc., Japan, and the system by Berkeley Robotics Laboratory, Berkeley, CA (see Figure 9) [85] appear to be the first of a platoon of considerably more capable exoskeletons aimed at real-world uses that may soon, quite literally, be walking near you. Researchers are quick to mention other potential applications for their creations: Rescue and emergency personnel could use them to foray into debris-strewn or rugged terrain that no wheeled vehicle could negotiate; firefighters could carry heavy gear into burning buildings and injured people out of them; and furniture movers, construction workers and warehouse attendants could lift and carry heavier objects safely. Research on upper-limb exoskeletons is also emerging [23]. The envisaged application is to assist the motion of weak persons in daily activity and rehabilitation.

Conclusion

Since the introduction of industrial robots in the automotive industry, robotics research has evolved over time towards the development of robotic systems to help the human in dangerous, risky or unpleasant tasks. As the complexity of tasks has increased, flexibility has been demanded in industrial robots, and robotics research has veered towards adaptive and intelligent systems.

Since 1995, robotics research has entered the field- and service-robotics world, where we can find manipulators, mobile robots and animal-like robots with great perspectives of development and increasing research interest. Surgical robots have been the first successes, and recently different areas in medical- and rehabilitation-robotics applications have arisen. Other examples can be found in the fields of home cleaning, refueling and museum exhibitions, to name just a few areas.

Service-robotics research is also aimed at providing a comfortable, easy life for the human being in an aging world. The United Nations Economic Commission for Europe (UNECE) forecasts strong growth of professional robots in application areas such as humanoid robots, field robots, underwater systems and mobile robot platforms for multiple use in the period of 2005–2008 [86]. The UNECE also forecasts a tremendous rise in personal robots in the next few years. Robotics research has to make a great effort to solve in very few years the challenges of this new field of research, which will be largely determined by interaction between humans and robots. Figure 10 summarizes the evolution of robotics research over the last 50 years.

It is a fact that, during the last decade, the activity in conferences and expositions all over the world has reflected low activity in industrial manipulators and huge activity in other areas related with manipulation in unstructured environments and mobility, including wheeled, flying, underwater, legged and humanoid robots. Maybe the key is that new challenges in manipulation in factories require less research now because factory needs lie in the field of traditional engineering.

With these premises we can conclude: Yes, definitely robotics research is moving from industrial to field and

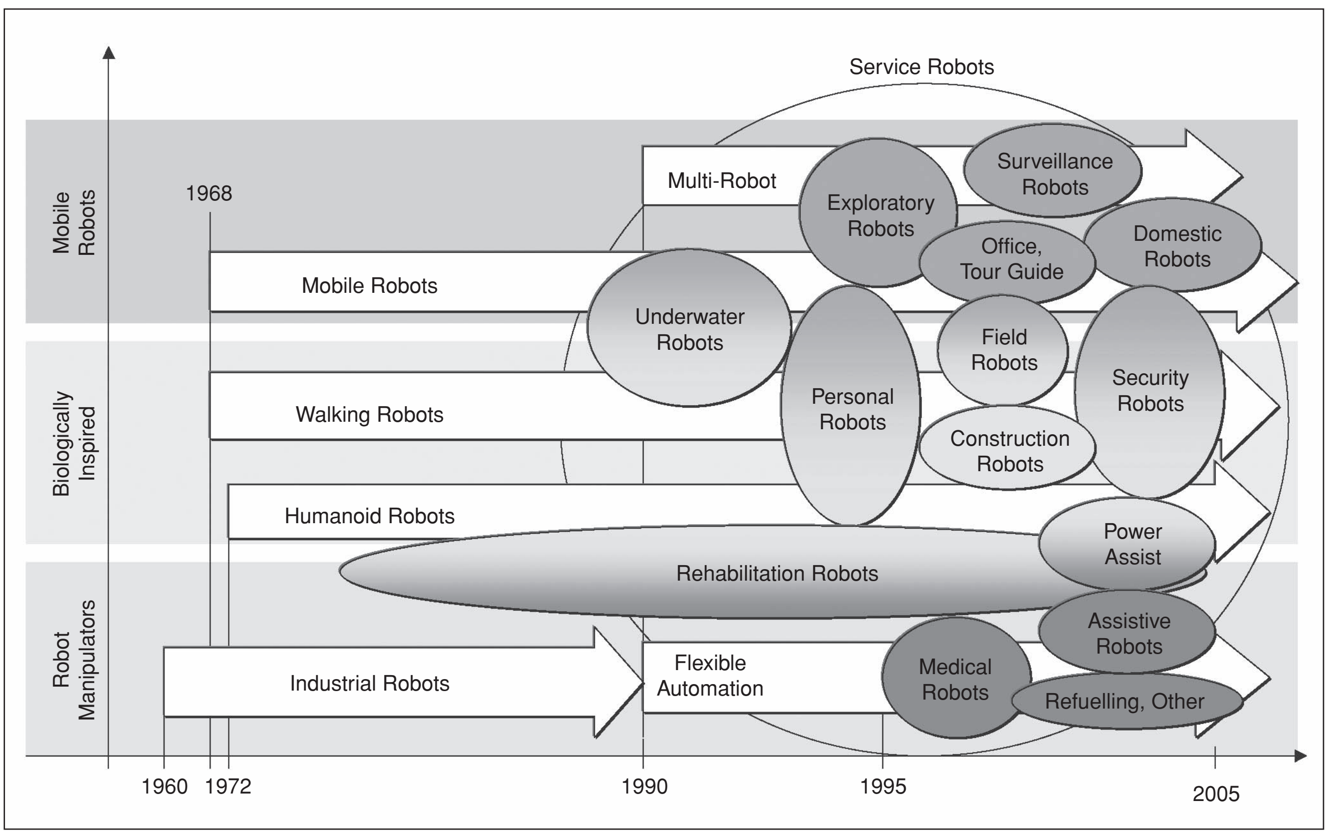


Figure 10. *Time evolution of the robotics research towards service robots.*

service applications, and most robotics researchers are enthusiastic about this broad, exciting field. One development that is very representative of the way the field is evolving is the controversy set off by Prof. Engelberger, the creator of the first robotics company, at the 2005 International Robot Exhibition in Tokyo, Japan, when he commented on the needless research by both Japanese companies and scientific institutions for developing toy-like animal and humanoid robots for very doubtful use. Engelberger thus gained many detractors, who have rapidly argued back that these kinds of robots are a necessary step in the evolution towards real robots capable of helping disabled persons, performing dangerous work and moving in hazardous places.

Other defenders of the development of human-like personal robots advocate the importance of aiming at such challenging tasks because of the technology that can be developed, which would prove very important from the commercial point of view in other industrial activities.

Maybe behind all the arguments there still lies the human dream of the universal robot—a single device that can perform any task. Nothing better for that than a device resembling—what else?—a human being. So, let our imagination fly into the world of service robotics, but, please, do not forget to keep an eye on traditional industrial manipulators.

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Keywords

Field robots, humanoid robots, industrial robots, medical robots, mobile robots, rehabilitation robots, robtoics, service robots, underwater robots, walking robotsservice robots.

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