Springer Handbook
of Robotics

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Springer Handbook
of Robotics

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Foreword

My first introduction to robotics came via a phone call in 1964. The caller was Fred Terman, the author of the world-famous *Radio Engineer's Handbook*, who was at the time Provost of Stanford University. Dr. Terman informed me that a computer science professor, John McCarthy, had just been awarded a large research grant, part of which required the development of computer-controlled manipulators. Someone had suggested to Terman that it would be prudent if the mathematically oriented McCarthy had some contact with mechanical designers. Since I was the only one on the Stanford faculty whose specialty was mechanism design, Terman decided to phone me, even though we had never met and I was a young assistant professor fresh out of graduate school with only 2 years at Stanford.

Dr. Terman's phone call led me to a close association with John McCarthy and the Stanford Artificial Intelligence Laboratory (SAIL) that he founded. Robotics became one of the pillars of my entire academic career, and I have maintained my interest in teaching and researching the subject through to the present day.

The modern history of robotic manipulation dates from the late 1940s when servoed arms were developed in connection with master–slave manipulator systems used to protect technicians handling nuclear materials. Developments in this area have continued to the present day. However, in the early 1960s there was very little academic or commercial activity in robotics. The first academic activity was the thesis of H. A. Ernst, in 1961, at MIT. He used a slave arm equipped with touch sensors, and ran it under computer control. The idea in his study was to use the information from the touch sensors to guide the arm.

This was followed by the SAIL project and a similar project started by Professor Marvin Minsky at MIT, which were the only sizeable academic ventures into robotics at that time. There were a few attempts at commercial manipulators, primarily in connection with part production in the automotive industry. In the USA there were two different manipulator designs that were being experimented with in the auto industry; one came from American Machine and Foundry (AMF) and the other from Unimation, Inc.

There were also a few mechanical devices developed as hand, leg, and arm prosthetics, and, a bit later, some exoskeletal devices to enhance human performance. In those days there were no microprocessors. So, these devices were either without computer control, or tethered to a remote so-called minicomputer, or even a mainframe computer.

Initially, some in the computer science community felt that computers were powerful enough to control any mechanical device and make it perform satisfactorily. We quickly learned that this was not to be the case. We started on a twofold track. One was to develop particular devices for SAIL, so that hardware demonstrations and proof-of-concept systems were available for the fledgling robotics community to experiment with. The other track, which was more or less moonlighted from the work at SAIL, was the development of a basic mechanical science of robotics. I had a strong feeling that a meaningful science could be developed, and that it would be best to think in terms of general concepts rather than concentrate exclusively on particular devices.

Fortuitously, it turned out that the two tracks supported each other very naturally and, most importantly, the right students were interested in doing their research in this area. Hardware developments proved to be specific examples of more general concepts, and the students were able to develop both the hardware and the theory.

Originally, we purchased an arm in order to get started quickly. A group at Rancho Los Amigos Hospital, in Los Angeles, was selling a tongue-switch-controlled motor-driven exoskeleton arm to assist patients without muscular control of their arms. We purchased one of these, and connected it to a time-shared PDP-6 computer. The device was named *Butterfingers*; it was our first experimental robot. Several films demonstrating visual feedback control, block stacking tasks, and obstacle avoidance were made with *Butterfingers* as the star performer.

The first manipulator that we designed on our own was known simply as the *Hydraulic Arm*. As its name implies, it was powered by hydraulics. The idea was

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to build a very fast arm. We designed special rotary actuators, and the arm worked well. It became the experimental platform for testing the first ever dynamic analysis and time-optimal control of a robotic arm. However, its use was limited since the design speeds were much faster than required due to the limitations of the computational, planning, and sensing capabilities that were common at that time.

We made an attempt to develop a truly digital arm. This led to a snake-like structure named the *Orm* (the Norwegian word for snake.) The *Orm* had several stages, each with an array of inflatable pneumatic actuators that were either fully extended or fully contracted. The basic idea was that, even though only a finite number of positions in the workspace could be reached, these would be sufficient if there were a large number of positions. A small prototype proof-of-concept *Orm* was developed. It led to the realization that this type of arm would not really serve the SAIL community.

The first truly functional arm from our group was designed by Victor Scheinman, who was a graduate student at the time. It was the very successful *Stanford Arm*, of which over ten copies were made as research tools to be used in various university, government, and industrial laboratories. The arm had six independently driven joints; all driven by computer-controlled servoed, DC electric motors. One joint was telescoping (prismatic) and the other five were rotary (revolute).

Whereas the geometry of *Butterfingers* required an iterative solution of the inverse kinematics, the geometric configuration of the *Stanford Arm* was chosen so that the inverse kinematics could be programmed in any easy-to-use time-efficient closed form. Furthermore, the mechanical design was specifically made to be compatible with the limitations inherent in timeshare computer control. Various end-effectors could be attached to act as hands. On our version, the hand was in the form of a vise-grip jaw, with two sliding fingers driven by a servoed actuator (hence, a true seventh degree of freedom). It also had a specially designed six-axis wrist force sensor. Victor Scheinman went on to develop other important robots: the first was a small humanoid arm with six revolute joints. The original design was paid for by Marvin Minsky at the MIT AI Lab. Scheinman founded Vicarm, a small company, and produced copies of this arm and the *Stanford Arm* for other labs. Vicarm later became the West Coast Division of Unimation, Inc., where Scheinman designed the *PUMA* manipulator under General Motors sponsorship through Unimation. Later, for a company called Automatix, Scheinman developed the novel *Robot World* multirobot system. After Scheinman

left Unimation, his colleagues Brian Carlisle and Bruce Shimano reorganized Unimation's West Coast Division into Adept, Inc., which to this day is the largest US manufacturer of assembly robots.

Quickly, the modern trend of carefully detailed mechanical and electronic design, optimized software, and complete system integration became the norm; to this day, this combination represents the hallmark of most highly regarded robotic devices. This is the basic concept behind *mechatronic*, a word conied in Japan as a concatenation of the words mechanics and electronics. Mechatronics that relies on computation is the essence of the technology inherent in robotics as we know it today.

As robotics developed around the world, a large number of people started working on various aspects, and specific subspecialties developed. The first big division was between people working on manipulators and those working on vision systems. Early on, vision systems seemed to hold more promise than any other method for giving robots information about their environment.

The idea was to have a television camera capture pictures of objects in the environment, and then use algorithms that allowed the computer images of the pictures to be analyzed, so as to infer required information about location, orientation, and other properties of objects. The initial successes with image systems were in problems dealing with positioning blocks, solving object manipulation problems, and reading assembly drawings. It was felt that vision held potential for use in robotic systems in connection with factory automation and space exploration. This led to research into software that would allow vision systems to recognize machine parts (particularly partially occluded parts, as occurred in the so-called "bin-picking" problems) and ragged-shaped rocks.

After the ability to "see" and move objects became established, the next logical need had to do with planning a sequence of events to accomplish a complex task. This led to the development of planning as an important branch in robotics. Making fixed plans for a known fixed environment is relatively straightforward. However, in robotics, one of the challenges is to let the robot discover its environment, and to modify its actions when the environment changes unexpectedly due to errors or unplanned events. Some early landmark studies in this area were carried out using a vehicle named *Shakey*, which, starting in 1966, was developed by Charlie Rosen's group at the Stanford Research Institute (now called SRI). *Shakey* had a TV camera, a trian-

gulating range finder, bump sensors, and was connected to DEC PDP-10 and PDP-15 computers via radio and video links.

Shakey was the first mobile robot to reason about its actions. It used programs that gave it the ability for independent perception, world modeling, and action generation. Low-level action routines took care of simple moving, turning, and route planning. Intermediate-level actions combined the low-level ones in ways that accomplished more complex tasks. The highest level programs could make and execute plans to achieve high-level goals supplied by a user.

Vision is very useful for navigation, locating objects, and determining their relative positions and orientation. However, it is usually not sufficient for assembling parts or working with robots where there are environmental constraining forces. This led to the need to measure the forces and torques generated by the environment, on a robot, and to use these measurements to control the robot's actions. For many years, force-controlled manipulation became one of the main topics of study at SAIL, and several other labs around the world. The use of force control in industrial practice has always lagged the research developments in this area. This seems to be due to the fact that, while a high level of force control is very useful for general manipulation issues, specific problems in very restricted industrial environments can often be handled with limited, or no, force control.

In the 1970s, specialized areas of study such as walking machines, hands, automated vehicles, sensor integration, and design for hostile environments began to develop rapidly. Today there are a large number of different specialties studied under the heading of robotics. Some of these specialties are classical engineering subject areas within which results have been developed that have been particularized to the types of machines called robots. Examples here are kinematics, dynamics, controls, machine design, topology, and trajectory planning. Each of these subjects has a long history predating the study of robotics; yet each has been an area of in-depth robotics research in order to develop its special character in regard to robotic-type systems and applications. In doing this specialized development, researchers have enriched the classical subjects by increasing both their content and scope.

At the same time that the theory was being developed, there was a parallel, although somewhat separate, growth of industrial robotics. Strong commercial development occurred in Japan and Europe, and there was also continued growth in the USA. Industrial associa-

tions were formed (the Japan Robot Association was formed in March 1971, and the Robotic Industries Association (RIA) was founded in 1974 in the USA) and trade shows, together with application-oriented technical sessions, were introduced and held on a regular basis. The most important were the International Symposium on Industrial Robots, the Conference on Industrial Robot Technology (now called the International Conference on Industrial Robot Technology), and the RIA annual trade show, which is now called the International Robots and Vision Show and Conference.

The first regular series of conferences emphasizing research, rather than the industrial, aspects of robotics, was inaugurated in 1973. It was sponsored jointly by the International Center for Mechanical Sciences (CISM), based in Udine, Italy, and the International Federation for the Theory of Mechanisms and Machines (IFToMM). (Although IFToMM is still used, its meaning has been changed to the International Federation for the Promotion of Mechanism and Machine Science.) It was named the Symposium on Theory and Practice of Robots and Manipulators (RoManSy). Its trademark was an emphasis on the mechanical sciences and the active participation of researchers from Eastern and Western Europe as well as North America and Japan. It is still held biannually. On a personal note, it is at RoManSy where I first met each of the editors of this Handbook: Dr. Khatib in 1978 and Dr. Siciliano in 1984. They were both students: Bruno Siciliano had been working on his PhD for about one year, and Oussama Khatib had just completed his PhD research. In both cases, it was love at first sight!

RoManSy was quickly joined by a host of other new conferences and workshops; today there are a large number of research oriented robotics meetings that take place through the year in many countries. Currently, the largest conference is the International Conference on Robotics and Automation (ICRA), which regularly draws well over 1000 participants.

In the beginning of the 1980s, the first real textbook on robotic manipulation in the USA was written by Richard "Lou" Paul (Richard P. Paul, *Robot Manipulators: Mathematics, Programming, and Control*, The MIT Press, Cambridge, MA, 1981). It used the idea of taking classical subjects in mechanics and applying them to robotics. In addition there were several topics developed directly from his thesis research at SAIL. (In the book, many examples are based on Scheinman's Stanford Arm.) Paul's book was a landmark event in the USA; it created a pattern for several influential future textbooks and also encouraged the creation of

specialized robotics courses at a host of colleges and universities.

At about this same time, new journals were created to deal primarily with research papers in the areas related to robotics. The *International Journal of Robotics Research* was founded in the spring of 1982, and three years later the *IEEE Journal of Robotics and Automation* (now the *IEEE Transactions on Robotics*) was founded.

As microprocessors became ubiquitous, the question of what is or is not a robot came more into play. This issue has, in my mind, never been successfully resolved. I do not think a definition will ever be universally agreed upon. There are of course the science fiction creatures-from-outer-space varieties, and the robots of the theater, literature, and the movies. There are examples of imaginary robot-like beings that predate the industrial revolution, but how about more down-to-Earth robots? In my view the definition is essentially a moving target that changes its character with technological progress. For example, when it was first developed, a ship's gyro auto-compass was considered a robot. Today, it is not generally included when we list the robots in our world. It has been demoted and is now considered an automatic control device.

For many, the idea of a robot includes the concept of multifunctionality, meaning the device is designed and built with the ability to be easily adapted or reprogrammed to do different tasks. In theory this idea is valid, but in practice it turns out that most robotic devices are multifunctional in only a very limited arena. In industry it was quickly discovered that a specialized machine, in general, performs much better than a general purpose machine. Furthermore, when the volume of production is high enough, a specialized machine can cost less to manufacture than a generalized one. So, specialized robots were developed for painting, riveting, quasiplanar parts assembly, press loading, circuit board stuffing, etc. In some cases robots are used in such specialized ways that it becomes difficult to draw the line between a so-called robot and an adjustable piece of "fixed" automation. Much of this practical unfolding is contrary to the dream of the pioneers in robotics, who had hoped for the development of general purpose machines that would do "everything", and hence sell in great enough volume to be relatively inexpensive.

My view is that the notion of a robot has to do with which activities are, at a given time, associated with people and which are associated with machines. If a machine suddenly becomes able to do what we normally associate with people, the machine can be upgraded in classification and classified as a robot. After a while,

people get used to the activity being done by machines, and the devices get downgraded from "robot" to "machine". Machines that do not have fixed bases, and those that have arm- or leg-like appendages have the advantage of being more likely called robots, but it is hard to think of a consistent set of criteria that fits all the current naming conventions.

In actuality any machines, including familiar household appliances, which have microprocessors directing their actions can be considered as robots. In addition to vacuum cleaners, there are washing machines, refrigerators, and dishwashers that could be easily marketed as robotic devices. There are of course a wide range of possibilities, including those machines that have sensory environmental feedback and decision-making capabilities. In actual practice, in devices considered to be robotic, the amount of sensory and decision making capability may vary from a great deal to none.

In recent decades the study of robotics has expanded from a discipline centered on the study of mechatronic devices to a much broader interdisciplinary subject. An example of this is the area called human-centered robotics. Here one deals with the interactions between humans and intelligent machines. This is a growing area where the study of the interactions between robots and humans has enlisted expertise from outside the classical robotics domain. Concepts such as emotions in both robots and people are being studied, and older areas such as human physiology and biology are being incorporated into the mainstream of robotics research. These activities enrich the field of robotics, as they introduce new engineering and science dimensions into the research discourse.

Originally, the nascent robotics community was focused on getting things to work. Many early devices were remarkable in that they worked at all, and little notice was taken of their limited performance. Today, we have sophisticated, reliable devices as part of the modern array of robotic systems. This progress is the result of the work of thousands of people throughout the world. A lot of this work took place in universities, government research laboratories, and companies. It is a tribute to the worldwide engineering and scientific community that it has been able to create the vast amount of information that is contained in the 64 chapters of this Handbook. Clearly these results did not arise by any central planning or by an overall orderly scheme. So the editors of this handbook were faced with the difficult task of organizing the material into a logical and coherent whole.

The editors have accomplished this by organizing the contributions into a three-layer structure. The first layer deals with the *foundations* of the subject. This layer consists of a single part of nine chapters in which the authors lay out the root subjects: kinematics, dynamics, control, mechanisms, architecture, programming, reasoning, and sensing. These are the basic technological building blocks for robotics study and development.

The second layer has four parts. The first of these deals with *robot structures*; these are the arms, legs, hands, and other parts that most robots are made up of. At first blush, the hardware of legs, arms, and hands may look quite different from each other, yet they share a common set of attributes that allows them to all be treated with the same, or closely related, aspects of the fundamentals described in the first layer.

The second part of this layer deals with *sensing and perception*, which are basic abilities any truly autonomous robotic system must have. As was pointed out earlier, in practice, many so-called robotic devices have little of these abilities, but clearly the more advanced robots cannot exist without them, and the trend is very much toward incorporating such capabilities into robotic devices. The third part of this layer treats the subject areas associated with the technology of *manipulation and the interfacing of devices*. The fourth part of this layer is made up of eight chapters that treat *mobile robots and various forms of distributed robotics*.

The third layer consists of two separate parts (a total of 22 chapters) that deal with advanced applications at the forefront of today's research and development. There are two parts to this layer; one deals with *field and service robots*, and the other deals with *human-centered and lifelike robots*. To the uninitiated observer, these chapters are what advanced robotics is all about. However, it is important to realize that many of these extraordinary accomplishments would probably not exist without the previous developments introduced in the first two layers of this Handbook.

It is this intimate connection between theory and practice that has nurtured the growth of robotics and become a hallmark of modern robotics. These two complementary aspects have been a source of great personal satisfaction to those of us who have had the opportunity to both research and develop robotic devices. The contents of this Handbook admirably reflect this complementary aspect of the subject, and present a very useful bringing together of the vast accomplishments which have taken place in the last 50 years. Certainly, the contents of this Handbook will serve as a valuable tool and guide to those who will produce the even more capable and diverse next generations of robotic devices. The editors and authors have my congratulations and admiration.

Stanford, August 2007   Bernard Roth

Foreword

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To open this Handbook and unfold the richness of its 64 chapters, we here attempt a brief personal overview to sketch the evolution of robotics in its many aspects, concepts, trends, and central issues.

The modern story of Robotics began about half a century ago with developments in two different directions.

First, let us acknowledge the domain of mechanical arms, ranging from teleoperated tasks on radiation-contaminated products to industrial arms, with the landmark machine UNIMATE – standing for uni(versal)mate. The industrial development of products, mostly around the six-degree-of-freedom serial links paradigm and active research and development, associating mechanical engineering to the control specialism, was the main driving force here. Of particular note nowadays is the successfully pursued effort to design novel application-optimized structures, using powerful sophisticated mathematical tools. In a similar way, an important issue concerns the design and the actual building of arms and hands in the context of human-friendly robots for tomorrow's cognitive robot.

Second, and less well recognized, we should acknowledge the stream of work concerned with themes in artificial intelligence. A landmark project in this area was the mobile robot *Shakey* developed at Stanford International. This work, which aimed to bring together computer science, artificial intelligence, and applied mathematics to develop intelligent machines, remained a secondary area for quite some time. During the 1980s, building strength from many study cases encompassing a spectacular spectrum ranging from rovers for extreme environments (planet exploration, Antarctica, etc.), to service robots (hospitals, museum guides, etc.), a broad research domain arose in which machines could claim the status of intelligent robots.

Hence robotics researches could bring together these two different branches, with intelligent robots categorized in a solely computational way as bounded rationality machines, expanding on the 1980s third-generation robot definition:

"(robot) ... operating in the three-dimensional world as a machine endowed with the capacity to interpret and to reason about a task and about its execution, by intelligently relating perception to action."

The field of autonomous robots, a widely recognized test-bed, has recently benefited from salient contributions in robot planning using the results of algorithmic geometry as well as of a stochastic framework approach applied both to environmental modeling and robot localization problems (SLAM, simultaneous localization and modeling), and further from the development of decisional procedures via Bayesian estimation and decision approaches.

For the last decade of the millennium, robotics largely dealt with the intelligent robot paradigm, blending together robots and machine-intelligence generic research within themes covering advanced sensing and perception, task reasoning and planning, operational and decisional autonomy, functional integration architectures, intelligent human–machine interfaces, safety, and dependability.

The second branch, for years referred to as non-manufacturing robotics, concerns a wide spectrum of research-driven real-world cases pertaining to field, service, assistive, and, later, personal robotics. Here, machine intelligence is, in its various themes, the central research direction, enabling the robot to act:

1. as a human surrogate, in particular for intervention tasks in remote and/or hostile environments
2. in close interaction with humans and operating in human environments in all applications encompassed by human-friendly robotics, also referred to as human-centered robotics
3. in tight synergy with the user, expanding from mechanical exoskeleton assistance, surgery, health care, and rehabilitation into human augmentation.

Consequently, at the turn of the millennium, robotics appears as a broad spectrum of research themes both supporting market products for well-engineered industrial workplaces, and a large number of domain-oriented application cases operating in hazardous and/or

harsh environments (underwater robotics, rough-terrain rovers, health/rehabilitation care robotics, etc.) where robots exhibit meaningful levels of shared autonomy.

The evolution levels for robotics stress the role of theoretical aspects, moving from application domains to the technical and scientific area. The organization of this Handbook illustrates very well these different levels. Furthermore, it rightly considers, besides a body of software systems, front-line matters on physical appearance and novel appendages, including legs, arms, and hands design in the context of human-friendly robots for tomorrow's cognitive robot.

Forefront robotics in the first decade of the current millennium is making outstanding progress, compounding the strength of two general directions:

● short/mid-term application-oriented study cases
● mid/long-term generic situated research

For completeness, we should mention the large number of peripheral, robotics-inspired subjects, quite often concerning entertainment, advertising, and sophisticated toys.

The salient field of human-friendly robotics encompasses several front-line application domains where the robots operate in a human environment and in close interaction with humans (entertainment and education, public-oriented services, assistive and personal robots, etc.), which introduces the critical issue of human–robot interaction.

Right at the core of the field, emerges the forefront topic of personal robots for which three general characteristics should be emphasized:

1. They may be operated by a nonprofessional user;
2. They may be designed to share high-level decision making with the human user;
3. They may include a link to environment devices and machine appendages, remote systems, and operators; the shared decisional autonomy concept (co-autonomy) implied here unfolds into a large set of cutting-edge research issues and ethical problems.

The concept of the personal robot, expanding to robot assistant and universal companion, is a truly great challenge for robotics as a scientific and technical field, offering the mid/long-term perspective of achieving a paramount societal and economical impact. This introduces, and questions, front-line topics encompassing cognitive aspects: user-tunable human–machine intelligent interfaces, perception (scene analysis, category identification), open-ended learning (understanding the universe of action), skills acquisition, extensive robot-world data processing, decisional autonomy, and dependability (safety, reliability, communication, and operating robustness).

There is an obvious synergistic effort between the two aforementioned approaches, in spite of the necessary framework time differences. The scientific link not only brings together the problems and obtained results but also creates a synergistic exchange between the two sides and the benefits of technological progress.

Indeed, the corresponding research trends and application developments are supported by an explosive evolution of enabling technologies: computer processing power, telecommunications, networking, sensing devices, knowledge retrieval, new materials, micro- and nanotechnologies.

Today, looking to the mid- and long-term future, we are faced with very positive issues and perspectives but also having to respond to critical comments and looming dangers for machines that are in physical contact with the user and may also be capable of unwanted, unsafe behavior. Therefore, there is a clear need to include at the research level safety issues and the topic of multifaced dependability and the corresponding system constraints.

The *Handbook of Robotics* is an ambitious and timely endeavor. It summarizes a large number of problems, questions, and facets considered by 164 authors in 64 chapters. As such it not only provides an efficient display of basic topics and results obtained by researches around the world, but furthermore gives access to this variety of viewpoints and approaches to everyone. This is indeed an important tool for progress but, much more, is the central factor that will establish the two first decades of this millennium as the dawn of robotics, lifted to a scientific discipline at the core of machine intelligence.

Toulouse, December 2007   Georges Giralt

Foreword

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The field of robotics was born in the middle of the last century when emerging computers were altering every field of science and engineering. Having gone through fast yet steady growth via a procession of stages from infancy, childhood, and adolescence to adulthood, robotics is now mature and is expected to enhance the quality of people's lives in society in the future.

In its infancy, the core of robotics consisted of pattern recognition, automatic control, and artificial intelligence. Taking on these new challenge, scientists and engineers in these fields gathered to investigate novel robotic sensors and actuators, planning and programming algorithms, and architectures to connect these components intelligently. In so doing, they created artifacts that could interact with humans in the real world. An integration of these early robotics studies yielded *hand–eye systems*, the test-bed of artificial intelligence research.

The playground for childhood robotics was the factory floor. Industrial robots were invented and introduced into the factory for automating spraying, spot welding, grinding, materials handling, and parts assembly. Machines with sensors and memories made the factory floor smarter, and its operations more flexible, reliable, and precise. Such robotic automation freed humans from heavy and tedious labor. The automobile, electric appliance, and semiconductor industries rapidly retooled their manufacturing lines into robot-integrated systems. In the late 1970s, the word *mechatronics*, originally coined by the Japanese, defined a new concept of machinery, one in which electronics was fused with mechanical systems, making a wide range of industrial products simpler, more functional, programmable, and intelligent. Robotics and mechatronics exerted an evolutionary impact on the design and operation of manufacturing processes as well as on manufactured products.

As robotics entered its adolescence, researchers were ambitious to explore new horizons. Kinematics, dynamics, and control system theory were refined and applied to real complex robot mechanisms. To plan and carry out real tasks, robots had to be made cognizant of their surroundings. Vision, the primary channel for external sensing, was exploited as the most general, effective, and efficient means for robots to understand their external situation. Advanced algorithms and powerful devices were developed to improve the speed and robustness of robot vision systems. Tactile and force sensing systems also needed to be developed for robots to manipulate objects. Studies on modeling, planning, knowledge, reasoning, and memorization expanded their intelligent properties. Robotics became defined as the study of intelligent connection of sensing to actuation. This definition covered all aspects of robotics: three scientific cores and one synthetic approach to integrate them. Indeed, system integration became a key aspect of robotic engineering as it allows the creation of lifelike machines. The fun of creating such robots attracted many students to the robotics field.

In advancing robotics further, scientific interest was directed at understanding humans. Comparative studies of humans and robots led to new approaches in scientific modeling of human functions. Cognitive robotics, lifelike behavior, biologically inspired robots, and a psychophysiological approach to robotic machines culminated in expanding the horizons of robotic potential. Generally speaking, an immature field is sparse in scientific understanding. Robotics in the 1980s and 1990s was in such a youthful stage, attracting a great many inquisitive researchers to this new frontier. Their continuous explorations into new realms form the rich scientific contents of this comprehensive volume.

Further challenges, along with expertise acquired on the cutting edge of robotics, opened the way to real-world applications for mature robotics. The early-stage playground gave way to a workshop for industrial robotics. Medical robotics, robot surgery, and in vivo imaging save patients from pain while providing doctors with powerful tools for conducting operations. New robots in such areas as rehabilitation, health care, and welfare are expected to improve quality of life in an aging society. It is the destiny of robots to go everywhere, in the air, under water, and into space. They are expected to work hand in hand with humans in such areas as agriculture, forestry, mining, construction, and hazardous environments and rescue operations, and to find

utility both in domestic work and in providing services in shops, stores, restaurants, and hospitals. In a myriad of ways, robotic devices are expected to support our daily lives. At this point, however, robot applications are largely limited to structured environments, where they are separated from humans for safety sake. In the next stage, their environment will be expanded to an unstructured world, one in which humans, as service takers, will always live and work beside robots. Improved sensing, more intelligence, enhanced safety, and better human understanding will be needed to prepare robots to function in such an environment. Not only technical but also social matters must be considered in finding solutions to issues impeding this progress.

Since my initial research to make a robot turn a crank, four decades have passed. I feel both lucky and happy to have witnessed the growth of robotics from its early beginnings. To give birth to robotics, fundamental technologies were imported from other disciplines. Neither textbooks nor handbooks were available. To reach the present stage, a great many scientists and engineers have challenged new frontiers; advancing robotics, they have enriched this body of knowledge from a variety of perspectives. The fruits of their endeavors are compiled in this *Handbook of Robotics*. More than 100 of the world's leading experts have collaborated in producing this publication. Now, people who wish to commit themselves to robotics research can find a firm foundation to build upon. This Handbook is sure to be used to further advance robotics science, reinforce engineering education, and systematically compile knowledge that will innovate both society and industry.

The roles of humans and robots in an aging society pose an important issue for scientists and engineers to consider. Can robotics contribute to securing peace, prosperity, and a greater quality of life? This is still an open question. However, recent advances in personal robots, robotic home appliances, and humanoids suggest a paradigm shift from the industrial to the service sector. To realize this, robotics must be addressed from such viewpoints as the working infrastructure within society, psychophysiology, law, economy, insurance, ethics, art, design, drama, and sports science. Future robotics should be studied as a subject that envelops both humanity and technology. This Handbook offers a selected technical foundation upon which to advance such newly emerging fields of robotics. I look forward to continuing progress adding page after page of robot-based prosperity to future society.

Tokyo, September 2007   Hirochika Inoue

Foreword

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Robots have fascinated people for thousands of years. Those automatons that were built before the 20th century did not connect sensing to action but rather operated through human agency or as repetitive machines. However, by the 1920s electronics had gotten to the stage that the first true robots that sensed the world and acted in it appropriately could be built. By 1950 we started to see descriptions of real robots appearing in popular magazines. By the 1960s industrial robots came onto the scene. Commercial pressures made them less and less responsive to their environments but faster and faster in what they did in their carefully engineered world. Then in the mid 1970s in France, Japan, and the USA we started to see robots rising again in a handful of research laboratories, and now we have arrived at a world-wide frenzy in research and the beginnings of large-scale deployment of intelligent robots throughout our world. This Handbook brings together the current state of robotics research in one place. It ranges from the mechanism of robots through sensing and perceptual processing, intelligence, action, and many application areas.

I have been more than fortunate to have lived with this revolution in robotics research over the last 30 years. As a teenager in Australia I built robots inspired by the tortoises of Walter described in the *Scientific American* in 1949 and 1950. When I arrived in Silicon Valley in 1977, just as the revolution in the personalization of computation was really coming into being, I instead turned to the much more obscure world of robots. In 1979 I was able to assist Hans Moravec at the Stanford Artificial Intelligence Lab (SAIL) as he coaxed his robot "The Cart" to navigate 20 m in 6 hours. Just 26 years later, in 2005, at the same laboratory, SAIL, Sebastian Thrun and his team coaxed their robot to autonomously drive 200,000 m in 6 hours: four orders of magnitude improvement in a mere 26 years, which is slightly better than a doubling every 2 years. However, robots have not

just improved in speed, they have also increased in number. When I arrived at SAIL in 1977 we knew of three mobile robots operating in the world. Recently a company that I founded manufactured its 3,000,000th mobile robot, and the pace is increasing. Other aspects of robots have had similarly spectacular advances, although it is harder to provide such crisp numeric characterizations. In recent years we have gone from robots being too unaware of their surroundings that it was unsafe for people to share their workspace to robots that people can work with in close contact, and from robots that were totally unaware of people to robots that pick up on natural social cues from facial expressions to prosody in people's voices. Recently robotics has crossed the divide between flesh and machines so that now we are seeing neuro-robotics ranging from prosthetic robotic extensions to rehabilitative robots for the disabled. And very recently robotics has become a respected contributor to research in cognitive science and neuroscience.

The research results chronicled in this volume give the key ideas that have enabled these spectacular advances. The editors, the part editors, and all the contributors have done a stellar job in bring this knowledge together in one place. Their efforts have produced a work that will provide a basis for much further research and development. Thank you, and congratulations to all who have labored on this pivotal book.

Some of the future robotics research will be incremental in nature, taking the state of the art and improving upon it. Other parts of future research will be more revolutionary, based on ideas that are antithetical to some of the ideas and current state of the art presented in this book.

As you study this volume and look for places to contribute to research through your own talents and hard work I want to alert you to capabilities or aspirations that I believe will make robots even more useful, more productive, and more accepted. I describe these capabilities in terms of the age at which a child has equivalent capabilities:

- the object-recognition capabilities of a 2-year-old child
- the language capabilities of a 4-year-old child

- the manual dexterity of a 6-year-old child
- the social understanding of an 8-year-old child

Each of these is a very difficult goal. However even small amounts of progress towards any one of these goals will have immediate applications to robots out in the world. Good reading and best wishes as you contribute further to robotkind.

Cambridge, October 2007   Rodney Brooks

Preface

Reaching for the human frontier, robotics is vigorously engaged in the growing challenges of new emerging domains. Interacting, exploring, and working with humans, the new generation of robots will increasingly touch people and their lives. The credible prospect of practical robots among humans is the result of the scientific endeavor of a half a century of robotic developments that established robotics as a modern scientific discipline.

The undertaking of the *Springer Handbook of Robotics* was motivated by the rapid growth of the field. With the ever increasing amount of publications in journals, conference proceedings and monographs, it is difficult for those involved in robotics, particularly those who are just entering the field, to stay abreast of its wide range of developments. This task is made even more arduous by the very multidisciplinary nature of robotics.

The handbook follows preceding efforts in the 1980s and 1990s, which have brought valuable references to the robotics community: Robot Motion: Planning and Control (Brady, Hollerbach, Johnson, Lozano-Pérez, and Mason, MIT Press 1982), Robotics Science (Brady, MIT Press 1989), The Robotics Review 1 and 2 (Khatib, Craig, and Lozano-Pérez, MIT Press 1989 and 1992). With the greater expansion of the robotics field and its increased outreach towards other scientific disciplines, the need for a comprehensive reference source combining basic and advanced developments has naturally become yet more urgent.

The volume is the result of the effort by a number of contributors who themselves are actively involved in robotics research in countries around the world. It has been a gigantic task to insightfully provide coverage of all the areas of robotics by such a motivated and versatile group of individuals committed to this endeavour.

The project started in May 2002 during a meeting the two of us had with Springer Director Engineering Europe Dieter Merkle and STAR Senior Editor Thomas Ditzinger. A year earlier, together with Frans Groen, we had launched the Springer Tracts in Advanced Robotics (STAR) series, which was rapidly establishing itself as an important medium for the timely dissemination of robotics research.

It was in this context that we took on this challenging task and enthusiastically began the planning to develop the technical structure and build the group of contributors. To capture the multiple dimensions of the field in its well-established academic core, ongoing research developments, and emerging applications, we conceived the handbook in a three-layer structure for a total of seven parts.

The first layer and part is devoted to the robotics foundations. The consolidated methodologies and technologies are grouped in the four parts of the second layer, covering robot structures, sensing and perception, manipulation and interfaces, mobile and distributed robotics. The third layer includes the advanced applications in the two parts on field and service robotics, and human-centered and life-like robotics, respectively.

To develop each of these parts, we envisioned the establishment of an editorial team which could coordinate the authors' contributions to the various chapters. A year later our seven-member editorial team was formed: David Orin, Frank Park, Henrik Christensen, Makoto Kaneko, Raja Chatila, Alex Zelinsky and Daniela Rus. With the commitment of such a group of distinguished scholars, the handbook was granted quality, span, and balance in the scientific areas.

By early 2005, we assembled an authorship of more than one-hundred-and-fifty contributors. An internal web site was created to facilitate inter-part and chapter cross-references, and to pace the schedule for the development of the project. The contents were carefully tuned over the following year, and especially during the two full-day workshops held in the spring of 2005 and 2006, well attended by most of the authors.

Each chapter was peer reviewed by at least three independent reviewers, typically involving the part editor, and two authors of related chapters; and in some cases, included external experts in the field. Two review cycles were necessary, and even three in some cases. During the process, a few more authors were recruited whenever it was deemed necessary. Most chapters were finalized by the end of the summer of 2007, and the project was completed by the early spring of 2008 – generating, by that time, a record of over 10 000 emails in our folders. The result is an impressive collection of 64 chapters

over the 7 parts, contributed by 165 authors, with more than 1650 pages, 950 illustrations and 5500 references.

We are deeply thankful to the authors for their intellectual contributions, as well as to the reviewers and part editors for their conscientious work. We are indebted to Werner Skolaut, the Senior Manager of Springer Handbooks in Science and Engineering, who soon became a devoted member of our team with his painstaking support to technically editing the authors' typescripts and linking the editors' work with the copy editing and production of the handbook. We also wish to acknowledge the highly professional work by the Le-TeX staff, which re-typeset all the text, redrew and improved the many illustrations, while timely interacting with the authors during the proof-reading of the material.

Six years after its conception the handbook comes to light. Beyond its tutorial value for our community, it is our hope that it will serve as a useful source to attract new researchers to robotics and inspire decades of vibrant progress in this fascinating field. The completion of every endeavor also brings new exciting challenges; at such times, our fellows are always reminded to . . . keep the gradient ;-)

Napoli and Stanford   Bruno Siciliano
April 2008   Oussama Khatib

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List of Abbreviations

A

AAAI	American Association for Artificial Intelligence
ABA	articulated-body algorithm
ABRT	automated bus rapid transit
ACAS	airborne collision avoidance systems
ACC	adaptive cruise control
ACM	active cord mechanism
ACM	Association of Computing Machinery
ADAS	advanced driver assistance systems
ADL	activities of daily living
ADSL	asymmetric digital subscriber line
AGV	automated guided vehicles
AHS	advanced highway systems
AI	artificial intelligence
AIP	anterior interparietal area
AIS	artificial intelligence (AI) system
AISB	artificial intelligence and simulation o behavior
AIT	anterior inferotemporal cortex
AM	actuators for manipulation
AMA	artificial moral agents
AMD	autonomous mental development
ANSI	American National Standards Institute
AP	antipersonnel
APG	adjustable pattern generator
AR	augmented reality
ARAMIS	Space Application of Automation, Robotics and Machine Intelligence
ASCL	adaptive seek control logic
ASD	autism spectrum disorder
ASIC	application-specific integrated circuit
ASKA	receptionist robot
ASM	advanced servomanipulator
ASN	active sensor network
ASTRO	autonomous space transport robotic operations
ASV	adaptive suspension vehicle
AT	antitank
ATLSS	advanced technology for large structural systems
ATR	Advanced Telecommunications Research Institute International
AuRA	autonomous robot architecture
AUV	autonomous underwater vehicles
AV	antivehicle

B

BIOROB	biomimetic robotics
BLDC	brushless direct current
BLE	broadcast of local eligibility
BLEEX	Berkeley lower-extremity exoskeleton
BLUE	best linear unbiased estimator
BN	Bayes network
BRT	bus rapid transit

C

C/A	coarse-acquisition
CAM	computer-aided manufacturing
CAD	computer-aided design
CAE	computer-aided engineering
CALM	continuous air interface long and medium range
CAN	controller area network
CARD	computer-aided remote driving
CASPER	continuous activity scheduling, planning, execution and replanning
CAT	computer-aided tomography
CB	cluster bombs
CCD	charge-coupled devices
CCI	control command interpreter
CCP	coverage configuration protocol
CCT	conservative congruence transformation
CCW	counterclockwise
CE	computer ethics
CEA	Commission de Energie Atomique
CEBOT	cellular robot
CF	climbing fibers
CF	contact formation
CG	center of gravity
CGA	clinical gait analysis
CGI	common gateway interface
CIE	International Commission on Illumination
CIRCA	cooperative intelligent real-time control architecture
CIS	computer-integrated surgery
CLARAty	coupled layered architecture for robot autonomy
CLEaR	closed-loop execution and recovery
CLIK	closed-loop inverse kinematics
CMAC	cerebellar model articulation controller
CML	concurrent mapping and localization
CNC	computer numerical control
CNP	contract net protocol

CNT	carbon nanotubes
COG	center of gravity
CONE	Collaborative Observatory for Nature Environments
CONRO	configurable robot
COR	center of rotation
CORBA	common object request broker architecture
COV	characteristic output vector
CP	closest point
CP	complementarity problem
CP	cerebral palsy
CPG	central pattern generators
CPSR	computer professional for social responsibility
CRBA	composite-rigid-body algorithm
CRLB	Cramer–Rao lower bound
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSMA	carrier sense multiple access
CT	computed tomography
CTFM	continuous-transmission frequency-modulated
CTL	cut-to-length
CU	control unit
CVIS	cooperative vehicle infrastructure systems
CW	clockwise

D

DARPA	Defense Advanced Research Projects Agency
DARS	distributed autonomous robotics systems
DBNs	dynamic Bayesian networks
DD	differentially driven
DDF	decentralized data fusion
DeVAR	desktop vocational assistant robot
DFRA	distributed field robot architecture
DFT	discrete Fourier transform
DGA	Delegation Generale pour L'Armement
DH	Denavit–Hartenberg
DIO	digital input-output
DIRA	distributed robot architecture
DL	description logics
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DM2	distributed macro-mini actuation
DoD	Department of Defense
DOF	degree of freedom
DOG	difference of Gaussian
DOP	dilution of precision
DPN	dip-pen nanolithography
DRIE	deep reactive ion etching
DSM	dynamic state machine
DSO	Defense Sciences Office
DSRC	dedicated short-range communications

DVL	Doppler velocity log
DWA	dynamic window approach

E

EBA	extrastriate body part area
EBID	electron-beam-induced deposition
ECU	electronics controller unit
EDM	electrical discharge machining
EDM	electronic distance measuring
EEG	electroencephalogram
EGNOS	Euro Geostationary Navigation Overlay Service
EKF	extended Kalman filter
EM	expectation maximization
EMG	electromyography
EMS	electrical master–slave manipulators
ENSICA	Ecole Nationale Superieure des Constructions Aeronautiques
EO	elementary operators
EOD	explosive ordnance disposal
EP	exploratory procedures
EPFL	Ecole Polytechnique Fédérale de Lausanne
EPP	extended physiological proprioception
ERA	European robotic arm
ES	electrical stimulation
ESA	European Space Agency
ESL	execution support language
ETS	engineering test satellite
EVA	extravehicular activity

F

FARS	Fagg-Arbib-Rizzolatti-Sakata
FE	finite element
FESEM	field-emission SEM
FIFO	first-in first-out
fMRI	functional magnetic resonance imaging
FMS	flexible manufacturing systems
FNS	functional neural stimulation
FOPL	first-order predicate logic
FPGAs	field programmable gate array
FRI	foot rotating indicator
FSA	finite-state acceptors
FSM	finite-state machine
FSR	force sensing resistor
FST	finite-state transducer
FSW	feasible solution of wrench
FTTH	fiber to the home

G

GAS	global asymptotic stability
GBAS	ground-based augmentation systems
GCR	goal-contact relaxation

GDP	gross domestic product
GenoM	generator of modules
GEO	geostationary Earth orbit
GI	gastrointestinal
GICHD	Geneva International Center for Humanitarian Demining
GJM	generalized Jacobian matrix
GLS	Global Navigation Satellite System Landing System
GMM	Gaussian mixture model
GMR	Gaussian mixture regression
GNS	global navigation systems
GNSS	global navigation satellite system
GP	Gaussian processes
GPR	ground-penetrating radar
GPRS	general packet radio service
GPS	global positioning system
GRACE	graduate robot attending conference
GSD	geon structural description
GSI	Gadd's severity index
GUI	graphical user interface
GZMP	generalized ZMP

H

HAL	hybrid assisted limb
HAMMER	hierarchical attentive multiple models for execution and recognition
HCI	human computer interaction
HD	haptic device
HDSL	high data rate digital subscriber line
HEPA	semi-high efficiency-particulate airfilter
HF	hard-finger
HIC	head injury criterion
HIP	haptic interaction point
HJB	Hamilton–Jacobi–Bellman
HJI	Hamilton–Jacobi–Isaac
HMD	head-mounted display
HMM	hidden Markov model
HMX	high melting point explosives
HO	human operator
HRI	human–robot interaction
HRTEM	high-resolution transmission electron microscopes
HST	Hubble space telescope
HSTAMIDS	handheld standoff mine detection system
HTML	hypertext markup language
HTN	hierarchical task network

I

I/O	input/output
I3CON	industrialized, integrated, intelligent, construction

IA	instantaneous allocation
IAD	intelligent assist device
ICA	independent component analysis
ICBL	International Campaign to Ban Landmines
ICE	internet communications engine
ICP	iterative closest-point algorithm
ICR	instantaneous center of rotation
ICRA	International Conference on Robotics and Automation
ICT	information and communication technology
IDL	interface definition language
IE	information ethics
IED	improvised explosive device
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet engineering task force
IFRR	International Foundation of Robotics Research
iGPS	indoor GPS
IHIP	intermediate haptic interaction points
IK	inverse kinematics
ILP	inductive logic programming
ILS	instrument landing system
IMTS	intelligent multimode transit system
IMU	inertial measurement units
IOSS	input-output-to-state stability
IP	internet protocol
IPC	interprocess communication
ISO	International Organization for Standardization
ISP	internet service provider
ISS	input-to-state stability
IST	Information Society Technologies
IST	Instituto Superior Técnico
IT	intrinsic tactile
IT	inferotemporal
ITD	interaural time difference
IxTeT	indexed time table

J

JAUS	joint architecture for unmanned systems
JAXA	Japan space exploration agency
JDL	joint directors of the laboratories
JEMRMS	Japanese experiment module remote manipulator system
JHU	Johns Hopkins University
JND	just noticeable difference
JPL	Jet Propulsion Laboratory
JSIM	joint-space inertia matrix
JSP	Java Server Pages

K

KR	knowledge representation

L

LAAS	Laboratoire d'Analyse et d'Architecture des Systèmes
LADAR	laser radar or laser detection and ranging
LAN	local-area network
LARC	Lie algebra rank condition
LBL	long-baseline system
LCSP	linear constraint satisfaction program
LGN	lateral geniculate nucleus
LIDAR	light detection and ranging
LOS	line of sight
LP	linear program
LQG	linear quadratic Gaussian
LSS	logical sensor system
LVDT	linear variable differential transformer
LWR	locally weighted regression

M

MACA	Afghanistan Mine Action Center
MANET	mobile ad hoc network
MAP	maximum a posteriori probability
MBARI	Monterey Bay Aquarium Research Institute
MBE	molecular-beam epitaxy
MBS	mobile base system
MC	Monte Carlo
MCS	mission control system
MDP	Markovian decision process
MST	microsystem technology
MEMS	microelectromechanical systems
MER	Mars exploration rovers
MESUR	Mars environmental survey
MF	Mossy fibers
MIA	mechanical impedance adjuster
MIG	metal inert gas
MIMO	multi-input multi-output
MIR	mode identification and recovery
MIS	minimally invasive surgery
MITI	Ministry of International Trade and Industry
ML	maximum likelihood
ML	machine learning
MLE	maximum-likelihood estimation
MLS	multilevel surface map
MNS	mirror neuron system
MOCVD	metallo-organic chemical vapor deposition
MOMR	multiple operator multiple robot
MOSR	multiple operator single robot
MPC	model predictive control

MPFIM	multiple paired forward-inverse models
MPM	manipulator positioning mechanism
MR	multirobot tasks
MR	multiple reflection
MR	magnetorheological
MRAC	model reference adaptive control
MRI	magnetic resonance imaging
MRL	manipulator retention latch
MRSR	Mars rover sample return
MRTA	multirobot task allocation
MSAS	Multifunctional Satellite Augmentation System
MSER	maximally stable extremal regions
MSM	master–slave manipulator

N

MT	multitask
MT	medial temporal
MTBF	mean time between failure
MTRAN	modular transformer
NAP	nonaccidental properties
NASA	National Aeronautics and Space Agency
NASDA	National Space Development Agency of Japan
NASREM	NASA/NBS standard reference model
NBS	National Bureau of Standards
NCEA	National Center for Engineering in Agriculture
NCER	National Conference on Educational Robotics
ND	nearness diagram navigation
NDDS	network data distribution service
NEMO	network mobility
NEMS	nanoelectromechanical systems
NICT	National Institute of Information and Communications Technology
NIDRR	National Institute on Disability and Rehabilitation Research
NIMS	networked infomechanical systems
NIOSH	National Institute for Occupational Health and Safety
NMEA	National Marine Electronics Association
NN	neural networks
NPS	Naval Postgraduate School
NRM	nanorobotic manipulators
NURBS	non-uniform rational B-spline

O

OASIS	onboard autonomous science investigation system
OBSS	orbiter boom sensor system
OCU	operator control units
ODE	ordinary differential equation

OH&S	occupation health and safety
OLP	offline programming
OM	optical microscope
ORB	object request brokers
ORCCAD	open robot controller computer aided design
ORM	obstacle restriction method
ORU	orbital replacement unit
OSIM	operational-space inertia matrix

P

P&O	prosthetics and orthotics
PAPA	privacy, accuracy, intellectual property, and access
PAS	pseudo-amplitude scan
PB	parametric bias
PbD	programming by demonstration
PC	principal contact
PC	Purkinje cells
PCA	principle components analysis
PD	proportional-derivative
PDDL	planning domain description language
PDGF	power data grapple fixtures
PEAS	probing environment and adaptive sleeping protocol
PET	positron emission tomography
PF	parallel fibers
PFC	prefrontal cortex
PFM	potential field method
pHRI	physical human–robot interaction
PI	policy iteration
PIC	programmable interrupt controller
PIC	programmable intelligent computer
PID	proportional–integral–derivative
PIT	posterior inferotemporal cortex
PKM	parallel kinematic machine
PLC	programmable logic controller
PLD	programmable logic device
PLEXIL	plan execution interchange language
PMD	photonic mixer device
PMMA	polymethyl methacrylate
PNT	Petri net transducers
POMDP	partially observable MDP
PPRK	palm pilot robot kit
PPS	precise positioning system
PR	photoresist
PRISMA	Projects of Robotics for Industry and Services, Mechatronics and Automation
PRM	probabilistic roadmap method
PRN	pseudorandom noise
PRS	procedural reasoning system
PS	power source
PTP	point-to-point

PTU	pan–tilt unit
PVDF	polyvinyledene fluoride
PwoF	point-contact-without-friction
PZT	lead zirconate titanate

Q

QD	quantum dot
QRIO	quest for curiosity
QT	quasistatic telerobotics

R

R.U.R.	Rossum's Universal Robots
RAIM	receiver autonomous integrity monitoring
RALPH	rapidly adapting lane position handler
RAM	random-access (volatile) memory
RANSAC	random sample consensus
RAP	reactive action packages
RAS	Robotics and Automation Society
RBC	recognition-by-components
RBF	radial basis function
RC	radio-controlled
RCC	remote center of compliance
RCM	remote center of motion
RCR	responsible conduct of research
RCS	real-time control system
RERC	Rehabilitation Engineering Research Center on Rehabilitation Robotics
RF	radiofrequency
RFID	radiofrequency identification
RFWR	receptive field weighted regression
RG	rate gyros
RGB	red, green, blue
RIG	rate-integrating gyros
RL	reinforcement learning
RLG	random loop generator
RMMS	reconfigurable modular manipulator system
RNEA	recursive Newton–Euler algorithm
RNNPB	recurrent neural network with parametric bias
RNS	reaction null space
ROC	receiver operating curve
ROKVISS	robotic components verification on the ISS
ROM	read-only memory
ROTEX	robot technology experiment
ROV	remotely operated vehicle
RPC	remote procedure call
RPI	Rensselaer Polytechnic Institute
RPV	remotely piloted vehicle
RRT	rapid random tree
RSS	realistic robot simulation

RT	reaction time		SPDM	special-purpose dexterous manipulator
RT	room-temperature		SPS	standard position system
RTCA	Radio Technical Commission for Aeronautics		SR	single-robot
			SRMS	shuttle remote manipulator system
RTD	resistance temperature device		SSRMS	Space shuttle remote manipulator system
RTI	real-time innovations			
RTK	real-time kinematics		ST	single-task
RTS	real-time system		STM	scanning tunneling microscopes
RWI	real-world interface		STS	superior temporal sulcus
RWS	robotic work station		SVD	singular value decomposition
			SWNT	single-walled carbon nanotubes

S

SA	selective availability
SAIC	Science Applications International, Inc.
SAIL	Stanford Artificial Intelligence Laboratory
SAN	semiautonomous navigation
SBAS	satellite-based augmentation systems
SBL	short-baseline system
SCARA	selective compliance assembly robot arm
SCI	spinal cord injury
SDK	standard development kit
SDR	software for distributed robotics
SDV	spatial dynamic voting
SEA	series elastic actuator
SEE	standard end-effector
SELF	sensorized environment for life
SEM	scanning electron microscopes
SET	single-electron transistors
SF	soft-finger
SfM	structure from motion
SFX	sensor fusion effects
SGAS	semiglobal asymptotic stability
SGUUB	semiglobal uniform ultimate boundedness
SHOP	simple hierarchical ordered planner
SIFT	scale-invariant feature transformation
SIGMOD	Special Interest Group on Management of Data
SIPE	system for interactive planning and execution monitoring
SIR	sampling importance resampling
SISO	single-input single-output
SKM	serial kinematic machines
SLAM	simultaneous localization and mapping
SLAMP	sheep loading animal manipulation platform
SLICE	specification language for ICE
SLRV	surveyor lunar rover vehicle
SMA	shape-memory alloy
SMC	sequential Monte Carlo
SNOM	scanning near-field OM
SOI	silicon-on-insulator
SOMR	single operator multiple robot
SOSR	single operator single robot
SPA	sense–plan–act

T

TA	time-extended assignment
TAP	test action pairs
TC	technical committee
TCP	transmission control protocol
TDL	task description language
TDT	tension differential type
TEM	transmission electron microscopes
tEODor	telerob explosive ordnance disposal and observation robot
TF-IDF	term-frequency inverse document frequency
TMS	transcranial magnetic stimulation
TOF	time of flight
TPBVP	two-point boundary value problem
TSEE	teleoperated small emplacement excavator
TSP	telesensor programming
TTI	thoracic trauma index
TTS	text-to-speech

U

UAS	unmanned aerial systems
UAV	unmanned aerial vehicles
UDP	user data protocol
UGV	unmanned ground vehicle
UML	unified modeling language
URL	uniform resource locator
US	ultrasound
USBL	ultrashort-baseline system
USV	unmanned surface vehicle
UUB	uniform ultimate boundedness
UUV	unmanned underwater vehicles
UVMS	underwater vehicle manipulator system
UWB	ultra-wideband
UXO	unexploded ordnance

V

VANET	vehicular ad-hoc network
VC	viscous injury response
VCR	videocassette recorder

vdW	van der Waals	WAN	wide-area network
VFH	vector field histogram	WG	world graph
VI	value iteration	WMR	wheeled mobile robot
VIA	variable-impedance actuation	WMSD	work-related musculoskeletal disorders
VLSI	very-large-scale integrated	WTA	winner-take-all
VM	virtual manipulator	WWW	world wide web
VO	velocity obstacles		
VOR	vestibular-ocular reflex		
VOR	VHF omnidirectional range		
VR	virtual reality		
VRML	virtual reality modeling language		
VVV	versatile volumetric vision		

X

XHTML	extensible hyper text markup language
XML	extensible markup language

W

WABIAN	Waseda bipedal humanoid
WAM	whole-arm manipulator

Z

ZMP	zero-moment point
ZP	zona pellucida