Springer Handbook of Robotics

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Springer Handbook of Robotics

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With 1375 Figures and 109 Tables

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Foreword

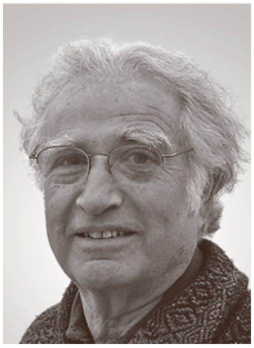
My first introduction to robotics came via a phone call in 1964. The caller was Fred Terman, the author of the world-famous *Radio Engineer's Handbook*, who was at the time Provost of Stanford University. Dr. Terman informed me that a computer science professor, John McCarthy, had just been awarded a 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.



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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 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 time-share 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 triangulating 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 associations 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

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.

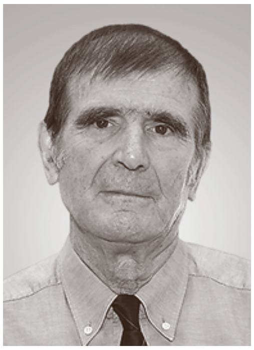
First, let us acknowledge the domain of mechanical arms, ranging from teleoperated tasks on radiation-contaminated products to industrial arms, with the landmark machine UNIMATE – standing for uni(versal)mate. The industrial development of products, mostly around the six-degree-of-freedom serial links 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.



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(deceased)

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

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.

Hirochika Inoue
Professor Emeritus
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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

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 neurorobotics 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.

Rodney Brooks
Panasonic Professor of Robotics
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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 to the Second Edition

The Springer Handbook of Robotics was a challenging six-year endeavour from 2002 to 2008. It mobilized a large number of active scientists and researchers to produce this unique comprehensive reference source combining basic and advanced developments. The handbook has been very successful and extremely well received in our community. New researchers have been attracted to robotics which in turn have contributed to further progress in this trans-disciplinary field.

The handbook soon established itself as a landmark in robotics publishing and beyond. It has been the bestseller of all Springer engineering books during the last seven years, the number one in chapter downloads (nearly forty thousand a year), and the fourth most downloaded over all Springer books in 2011. In February 2009, the handbook was recognized as the Winner of the American Association of Publishers (AAP) PROSE Award for Excellence in Physical Sciences & Mathematics as well as the Award for Engineering & Technology.

The rapid growth of our field as well as the birth of new research areas motivated us in 2011 to start pursuing a second edition with the intent to provide not only an update but also an expansion of the handbook's contents. Our editorial board (with David Orin, Frank Park, Henrik Christensen, Makoto Kaneko, Raja Chatila, Alex Zelinsky, and Daniela Rus) has been enthusiastically engaged during the last four years to coordinate the contributions of the authors to the seven parts of the handbook in its three-layer structure. The contents have been restructured to achieve four main objectives: the enlargement of foundational topics for robotics, the enlightenment of design of various types of robotic systems, the extension of the treatment on robots moving in the environment, and the enrichment of advanced robotics applications. Most previous chapters have been revised, fifteen new chapters have been introduced on emerging topics, and a new generation of authors have joined the handbook's team. The contents were finalized by the spring of 2015 after extensive review and feedback, and the project was completed by the fall of 2015 – generating, by that time, a record of over 12 000 additional emails in our folders to the 10 000 of the first edition. The result is an impressive collection of 80 chapters over the 7 parts, contributed by 229 authors, with more than 2300 pages, 1375 illustrations and 9411 references.

One of the major additions of the second edition of the handbook is the inclusion of multimedia material. An editorial team has been established under the leadership of Torsten Kröger and the contributions of Gianluca Antonelli, Dongjun Lee, Dezhen Song and Stefano Stramigioli. With the commitment of such a group of energetic young scholars, the multimedia project has been pursued in parallel to the handbook project. The multimedia editorial team has selected for each chapter video contributions, from those suggested by the authors, based on their quality and relevance to the chapter's contents. In addition, the handbook editors have produced tutorial videos that can be accessed directly from each part of the handbook. An openly accessible multimedia website, http://handbookofrobotics.org, has been established to host these videos with the sponsorship of IEEE Robotics and Automation Society and Google. The website has been conceived as a live dissemination project bringing the latest robotics contributions to the world community.

We are deeply grateful for the continuous commitment of our handbook extended team, particularly the newcomers to the project. We would like to express our gratitude and appreciation to Judith Hinterberg, Werner Skolaut and Thomas Ditzinger from Springer for their strong support, as well as to Anne Strohbach and the le-tex staff for their highly professional typesetting work in the production.

Eight years after the first appearance of the handbook, the second edition comes to light. Beyond its tutorial value for our community, it is our conviction that the handbook will continue to serve as a useful source to attract new researchers to robotics and inspire decades of vibrant progress in this fascinating field. The cooperative spirit inspiring our team since the inception of the first edition is amusingly illustrated in the video *The Handbook – A Short History* (VIDEO 844). The completion of the second edition has been inspired by that same spirit and the gradient has been kept :-) Our fellows in the robotics community are reminded now to ... keep the Hessian ;-)

January 2016
Bruno Siciliano, Naples
Oussama Khatib, Stanford

Preface to the Multimedia Extension

Scientific and technical advancements in the domain of robotics have accelerated significantly over the past decade. Since the inception of the Second Edition of the Springer Handbook of Robotics in 2011, the Editors Bruno Siciliano and Oussama Khatib decided to add multimedia content and appointed an editorial team: Gianluca Antonelli, Dongjun Lee, Dezhen Song, Stefano Stramigioli, and myself as the Multimedia Editor.

Over the five years of the project, everyone on the team worked with all of the 229 authors, the Part Editors, and the Editors. Besides communicating with all 80 Authors' teams and reviewing, selecting, and improving all video contributions, we also scanned all the videos published at robotics conferences organized by the IEEE Robotics and Automation Society since 1991. A total of more than 5500 e-mails were sent back and forth to coordinate the project and to ensure the quality of the content. We implemented a video management system that allows authors to upload videos, editors to review videos, and readers to access videos. Videos were selected with the goal of helping convey content to all readers of the Second Edition. They may be relevant from a technical, scientific, educational, or historical perspective. All chapter and part videos are publicly accessible and can be found at

http://handbookofrobotics.org

In addition to the videos referenced in the chapters, each of the seven parts is accompanied by a part video giving an overview of each part. The storyboards of these videos were created by the Part Editors and then professionally produced.

The video content provided in the Multimedia Extension makes understanding the written content easier and was designed to be a comprehensive addition to the Handbook. Concepts, methods, experiments, and applications described in the book were animated, visually illustrated, or paired with sound and narration – giving readers a further dimension to comprehend the written content of the book.

Coordinating the work with more than 200 contributors cannot just be done by a small team, and we are deeply grateful for the support of many people and organizations. Judith Hinterberg and Thomas Ditzinger from the Springer Team in Heidelberg helped us tremendously with professional support during the entire production phase. The app for smartphones and tablets was implemented by Rob Baldwin from Studio Orb and allows readers easy access to multimedia content. The IEEE Robotics and Automation Society granted permissions to use all videos that have been published in the proceedings of conferences sponsored by the society. Google and X supported us by donating funds for the implementation of the website backend.

Following the Editors' inspiration, let us keep working and communicating as one community – and let us keep the Hessian all together . . . !

March 2016
Torsten Kröger Mountain View

Accessing Multimedia Contents

Multimedia contents are an integral part of the Second Edition of the Springer Handbook of Robotics. 69 chapters contain video icons like this one:

VIDEO 843

Each icon indicates a video ID that can be used to access individual videos in various simple and intuitive ways.

Using the Multimedia App

We recommend using the multimedia app for smartphone and tablet PCs. You can install the app on *iOS* and *Android* devices using the QR code below. The app allows you to simply scan the pages of the book and automatically play all videos on your device while reading the book.

Multimedia Contents

Using the Website: http://handbookofrobotics.org

All chapter videos and part videos can be accessed directly from the website of the multimedia extension. Just enter a video ID in the search field in the top right corner of the website. You may also use the website to browse through chapter and part videos.

Using PDF Files

If you read an electronic copy of the Handbook, each video icon contains a hyper link. Just click on the link to watch the corresponding video.

Using QR Codes

Each chapter starts with a QR code that contains a link to all videos of the chapter. Part videos can be accessed through the QR code at the beginning of each part.

About the Editors

Bruno Siciliano received his Doctorate degree in Electronic Engineering from the University of Naples, Italy, in 1987. He is Professor of Control and Robotics at University of Naples Federico II. His research focuses on methodologies and technologies in industrial and service robotics including force and visual control, cooperative robots, human-robot interaction, and aerial manipulation. He has co-authored 6 books and over 300 journal papers, conference papers and book chapters. He has delivered over 20 keynote presentations and over 100 colloquia and seminars at institutions around the world. He is a Fellow of IEEE, ASME and IFAC. He is Co-Editor of the Springer Tracts in Advanced Robotics (STAR) series and the Springer Handbook of Robotics, which received the PROSE Award for Excellence in Physical Sciences & Mathematics and was also the winner in the category Engineering & Technology. He has served on the Editorial Boards of prestigious journals, as well as Chair or Co-Chair for numerous international conferences. Professor Siciliano is the Past-President of the IEEE Robotics and Automation Society (RAS). He has been the recipient of several awards, including the IEEE RAS George Saridis Leadership Award in Robotics and Automation and the IEEE RAS Distinguished Service Award.

Oussama Khatib received his Doctorate degree in Electrical Engineering from Sup'Aero, Toulouse, France, in 1980. He is Professor of Computer Science at Stanford University. His research focuses on methodologies and technologies in human-centered robotics including humanoid control architectures, human motion synthesis, interactive dynamic simulation, haptics, and human-friendly robot design. He has co-authored over 300 journal papers, conference papers and book chapters. He has delivered over 100 keynote presentations and several hundreds of colloquia and seminars at institutions around the world. He is a Fellow of IEEE. He is Co-Editor of the Springer Tracts in Advanced Robotics (STAR) series and the Springer Handbook of Robotics, which received the PROSE Award for Excellence in Physical Sciences & Mathematics and was also the winner in the category Engineering & Technology. He has served on the Editorial Boards of prestigious journals, as well as Chair or Co-Chair for numerous international conferences. Professor Khatib is the President of the International Foundation of Robotics Research. He has been the recipient of several awards, including the IEEE RAS Pioneer Award in Robotics and Automation, the IEEE RAS George Saridis Leadership Award in Robotics and Automation, the IEEE RAS Distinguished Service Award, and the Japan Robot Association (JARA) Award in Research and Development.

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Contents

Part D Manipulation and Interfaces

Part E Moving in the Environment

List of Abbreviations

Symbols

k-NN	*k*-nearest neighbor
0-D	zero-dimensional
1-D	one-dimensional
2-D	two-dimensional
2.5-D	two-and-a-half-dimensional
3-D	three-dimensional
3-D-NDT	three-dimensional!normal distributions transform
4-D	four-dimensional
6-D	six-dimensional
6R	six-revolute
7R	seven-revolute

A

A&F	agriculture and forestry
AA	agonist–antagonist
AAAI	American Association for Artificial Intelligence
AAAI	Association for the Advancement of Artificial Intelligence
AAL	ambient assisted living
ABA	articulated-body algorithm
ABF	artificial bacterial flagella
ABRT	automated!bus rapid transit
ABS	acrylonitrile–butadiene–styrene
AC	aerodynamic center
AC	alternating current
ACARP	Australian Coal Association Research Program
ACBS	automatic!constructions building system
ACC	adaptive cruise control
ACFV	autonomous!combat flying vehicle
ACM	active chord mechanism
ACM	active cord mechanism
ACT	anatomically correct testbed
ADAS	advanced driving assistance system
ADC	analog digital conveter
ADCP	acoustic Doppler current profiler
ADL	activities for daily living
ADSL	asymmetric digital subscriber line
AFC	alkaline fuel cell
AFC	armoured (or articulated) face conveyor
AFM	atomic force microscope
AFV	autonomous!flying vehicle
AGV	autonomous guided vehicle
AGV	automated!guided vehicle
AHRS	attitude and heading reference system
AHS	advanced highway system
AI	artificial intelligence
AIAA	American Institute of Aeronautics and Astronautics
AIM	assembly incidence matrix
AIP	air-independent power
AIP	anterior intraparietal sulcus
AIP	anterior interparietal area
AIS	artificial intelligence system
AIST	Institute of Advanced Industrial Science and Technology
AIST	Japan National Institute of Advanced Industrial Science and Technology
AIST	National Institute of Advanced Industrial Science and Technology (Japan)
AIT	anterior inferotemporal cortex
ALEX	active leg exoskeleton
AM	actuator for manipulation
AMASC	actuator with mechanically adjustable series compliance
AMC	Association for Computing Machinery
AMD	autonomous!mental development
AMM	audio-motor map
ANN	artificial neural network
AO	Arbeitsgemeinschaft für Ostheosynthesefragen
AOA	angle of attack
AP	antipersonnel
APF	annealed particle filter
APG	adjustable pattern generator
API	application programming interface
APOC	allowing dynamic selection and changes
AR	autoregressive
aRDnet	agile robot development network
ARM	Acorn RISC machine architecture
ARM	assistive!robot service manipulator
ARX	auto regressive estimator
ASAP	adaptive sampling and prediction
ASCII	American standard code for information interchange
ASD	autism spectrum disorder
ASIC	application-specific integrated circuit
ASIC	application-specific feature transform
ASIMO	advanced step in innovative mobility
ASK	amplitude shift keying
ASL	autonomous systems laboratory
ASM	advanced servomanipulator

ASN	active sensor network
ASR	automatic!spoken-language recognition
ASR	automatic!speech recognition
ASTRO	autonomous!space transport robotic operations
ASV	adaptive suspension vehicle
ASyMTRe	automated!synthesis of multirobot task solutions through software reconfiguration
AT	anti-tank mine
ATHLETE	all-terrain hex-legged extra-terrestrial explorer
ATLANTIS	a three layer architecture for navigating through intricate situations
ATLSS	advanced technology for large structural systems
ATR	automatic!target recognition
AuRA	autonomous robot architecture
AUV	autonomous underwater vehicle
AUV	autonomous aquatic vehicle
AUVAC	Autonomous Undersea Vehicles Application Center
AUVSI	Association for Unmanned Vehicle Systems International
AV	anti-vehicle

B

B/S	browser/server
B2B	business to business
BCI	brain-computer interface
BE	body extender
BEMT	blade element momentum theory
BEST	boosting!engineering science and technology
BET	blade element theory
BFA	bending fluidic actuator
BFP	best-first-planner
BI	brain imaging
BIP	behavior-interaction-priority
BLE	broadcast of local eligibility
BLEEX	Berkely exoskeleton
BLUE	best linear unbiased estimator
BML	behavior!mark-up language
BMS	battery management system
BN	Bayesian network
BOM	bill of material
BOw	bag-of-word
BP	behavior primitive
BP	base plate
BRICS	best practice in robotics
BRT	bus rapid transit
BWSTT	body-weight supported treadmill training

C

C	cylindrical joint
C/A	coarse-acquisition
C/S	client/server
CA	collision avoidance
CACC	cooperative adaptive cruise control
CAD	computer-aided drafting
CAD	computer-aided design
CAE	computer-aided engineering
CALM	communication access for land mobiles
CAM	computer-aided manufacturing
CAN	controller area network
CARD	computer-aided remote driving
CARE	coordination action for robotics in Europe
CASA	Civil Aviation Safety Authority
CASALA	Centre for Affective Solutions for Ambient Living Awareness
CASPER	continuous activity scheduling, planning, execution and replanning
CAT	collision avoidance technology
CAT	computer-aided tomography
CB	computional brain
CB	cluster bomb
CBRNE	chemical, biological, nuclear, radiological, or explosive
CC	compression criterion
CCD	charge-coupled device
CCD	charge-coupled detector
CCI	control command interpreter
CCP	coverage configuration protocol
CCT	conservative congruence transformation
CCW	counterclockwise
CC&D	camouflage, concealment, and deception
CD	collision detection
CD	committee draft
CD	compact disc
CDC	cardinal direction calculus
CDOM	colored dissolved organic matter
CE	computer ethic
CEA	Commissariat à l'Énergie Atomique
CEA	Atomic Energy Commission
CEBOT	cellular robotic system
CEC	Congress on Evolutionary Computation
CEPE	Computer Ethics Philosophical Enquiry
CES	Consumer Electronics Show
CF	carbon fiber
CF	contact formation
CF	climbing fiber
CFD	computational fluid dynamics
CFRP	carbon fiber reinforced prepreg
CFRP	carbon fiber reinforced plastic
CG	center of gravity

CG	computer graphics
CGI	common gateway interface
CHMM	coupled!hidden Markov model
CHMM	continuous hidden Markov model
CIC	computer integrated construction
CIE	International Commission on Illumination
CIP	Children's Innovation Project
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
CMCs	ceramic matrix composite
CML	concurrent!mapping and localization
CMM	coordinate measurement machine
CMOMMT	cooperative multirobot observation of multiple moving target
CMOS	complementary metal-oxide-semiconductor
CMP	centroid moment pivot
CMTE	Cooperative Research Centre for Mining Technology and Equipment
CMU	Carnegie Mellon University
CNC	computer numerical control
CNN	convolutional neural network
CNP	contract net protocol
CNRS	Centre National de la Recherche Scientifique
CNT	carbon nanotube
COCO	common objects in context
COG	center of gravity
COM	center of mass
COMAN	compliant humanoid platform
COMEST	Commission mondiale d'éthique des connaissances scientifiques et des technologies
COMINT	communication intelligence
CONE	Collaborative Observatory for Nature Environments
COP	center of pressure
CoP	center of pressure
COR	center of rotation
CORBA	common object request broker architecture
CORS	continuous operating reference station
COT	cost!of transport
COTS	commercial off-the-shelf
COV	characteristic output vector
CP	complementarity problem
CP	capture point
CP	continuous path
CP	cerebral palsy
CPG	central pattern generation
CPG	central pattern generator
CPS	cyber physical system
CPSR	Computer Professional for Social Responsibility
CPU	central processing unit
CRASAR	Center for Robot-Assisted Search and Rescue
CRBA	composite-rigid-body algorithm
CRF	conditional random field
CRLB	Cramér–Rao lower bound
CSAIL	Computer Science and Artificial Intelligence Laboratory
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSMA	carrier-sense multiple-access
CSP	constraint satisfaction problem
CSSF	Canadian Scientific Submersile Facility
CT	computed tomography
CTFM	continuous-transmission frequency modulation
CU	control unit
cv-SLAM	ceiling vision SLAM
CVD	chemical vapor deposition
CVIS	cooperative vehicle infrastructure system
CVT	continuous variable transmission
CW	clockwise
CWS	contact!wrench sum

D

D	distal
D/A	digital-to-analog
DAC	digital analog converter
DARPA	Defense Advanced Research Projects Agency
DARS	distributed!autonomous robotic systems
DBN	dynamic Bayesian network
DBN	deep belief network
DC	disconnected
DC	direct current
DC	dynamic!constrained
DCS	dynamic covariance scaling
DCT	discrete!cosine transform
DD	differentially driven
DDD	dangerous, dirty, and dreary
DDF	decentralized data fusion
DDP	differential dynamic programming
DDS	data distribution service
DEA	differential elastic actuator
DEM	discrete!element method

DFA	design!for assembly
DFRA	distributed field robot architecture
DFT	discrete Fourier transform
DGPS	differential global positioning system
DH	Denavit–Hartenberg
DHMM	discrete!hidden Markov model
DHS	US Department of Homeland Security
DIRA	distributed!robot architecture
DIST	Dipartmento di Informatica Sistemica e Telematica
DL	description logic
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DLR	German Aerospace Center
DMFC	direct methanol fuel cell
DMP	dynamic movement primitive
DNA	deoxyribonucleic acid
DNF	dynamic!neural field
DOD	Department of Defense
DOF	degree of freedom
DOG	difference of Gaussian
DOP	dilution of precision
DPLL	Davis–Putnam algorithm
DPM	deformable part model
DPN	dip-pen nanolithography
DPSK	differential phase shift keying
DRIE	deep reactive ion etching
DSM	dynamic!state machine
DSO	Defense Sciences Office
DSP	digital signal processor
DSRC	dedicated short-range communications
DU	dynamic!unconstrained
DVL	Doppler velocity log
DWA	dynamic window approach
DWDM	dense wave division multiplex
D&D	deactivation and decommissioning

E

e-beam	electron-beam
EAP	electroactive polymer
EBA	energy bounding algorithm
EBA	extrastriate body part area
EBID	electron-beam induced deposition
EC	externally connected
EC	exteroception
ECAI	European Conference on Artificial Intelligence
ECD	eddy current damper
ECEF	earth-centred, earth-fixed
ECER	European Conference on Educational Robotics
ECG	electrocardiogram
ECU	electronics controller unit
EDM	electrical discharge machining
EE	end-effector
EEG	electroencephalography
EGNOS	European Geostationary Navigation Overlay Service
EHC	enhanced horizon control
EHPA	exoskeleton!for human performance augmentation
EKF	extended Kalman filter
ELS	ethical, legal and societal
EM	expectation maximization
emf	electromotive force
EMG	electromyography
EMIB	emotion, motivation and intentional behavior
EMS	electrical!master–slave manipulator
EO	electrooptical
EO	elementary operator
EOA	end of arm
EOD	explosive!ordnance disposal
EP	exploratory procedure
EP	energy packet
EPFL	Ecole Polytechnique Fédérale de Lausanne
EPP	extended!physiological proprioception
EPS	expandable polystyrene
ER	electrorheological
ER	evolutionary!robotics
ERA	European robotic arm
ERP	enterprise resource planning
ERSP	evolution robotics software platform
ES	electrical!stimulation
ESA	European Space Agency
ESC	electronic speed controller
ESL	execution support language
ESM	energy!stability margin
ESM	electric support measure
ETL	Electro-Technical Laboratory
ETS-VII	Engineering Test Satellite VII
EU	European Union
EURON	European Robotics Research Network
EVA	extravehicular activity
EVRYON	evolving morphologies for human–robot symbiotic interaction

F

F5	frontal area 5
FAA	Federal Aviation Administration
FAO	Food and Agriculture Organization
FARS	Fagg–Arbib–Rizzolatti–Sakata
FARSA	framework for autonomous robotics simulation and analysis

fastSLAM	fast simultaneous localization and mapping
FB-EHPA	full-body EHPA
FCU	flight control-unit
FD	friction damper
FDA	US Food and Drug Association
FDM	fused deposition modeling
FE	finite element
FEA	finite element analysis
FEM	finite element method
FESEM	field-emission SEM
FF	fast forward
FFI	Norwegian defense research establishment
FFT	fast Fourier transform
FIFO	first-in first-out
FIRA	Federation of International Robot-soccer Association
FIRRE	family of integrated rapid response equipment
FIRST	For Inspiration and Recognition of Science and Technology
Fl-UAS	flapping wing unmanned aerial system
FLIR	forward!looking infrared
FMBT	feasible minimum buffering time
FMCW	frequency modulation continuous wave
fMRI	functional!magnetic resonance imaging
FMS	flexible!manufacturing system
FNS	functional!neural stimulation
FOA	focus of attention
FOG	fiber-optic gyro
FOPEN	foliage penetration
FOPL	first-order predicate logic
FOV	field of view
FP	fusion primitive
FPGA	field-programmable gate array
FR	false range
FRI	foot rotation indicator
FRP	fiber-reinforced plastics
FRP	fiber-reinforced prepreg
fs	force!sensor
FSA	finite-state acceptor
FSK	frequency shift keying
FSR	force sensing resistor
FSW	friction!stir welding
FTTH	fiber to the home
FW	fixed-wing

G

GA	genetic algorithm
GAPP	goal as parallel programs
GARNICS	gardening with a cognitive system
GAS	global asymptotic stability
GBAS	ground based augmentation system
GCDC	Grand Cooperative Driving Challenge
GCER	Global Conference on Educational Robotics
GCR	goal-contact relaxation
GCS	ground!control station
GDP	gross!domestic product
GenoM	generator of modules
GEO	geostationary Earth orbit
GF	grapple fixture
GFRP	glass-fiber reinforced plastic
GI	gastrointestinal
GIB	GPS intelligent buoys
GICHD	Geneva International Centre for Humanitarian Demining
GID	geometric!intersection data
GIE	generalized-inertia ellipsoid
GIS	geographic information system
GJM	generalized!Jacobian matrix
GLONASS	globalnaya navigatsionnaya sputnikovaya sistema
GLS	global navigation satellite system
GMAW	gas-shielded metal arc welding
GMM	Gaussian mixture model
GMSK	Gaussian minimum shift keying
GMTI	ground!moving target indicator
GNC	guidance, navigation, and control
GO	golgi!tendon organ
GP	Gaussian process
GPCA	generalized principal component analysis
GPRS	general!packet radio service
GPS	global positioning system
GPU	graphics processing unit
GRAB	guaranteed recursive adaptive bounding
GRACE	graduate robot attending conference
GraWoLF	gradient-based win or learn fast
GSD	geon structural description
GSN	gait sensitivity norm
GSP	Gough–Stewart platform
GUI	graphical user interface
GV	ground vehicle
GVA	gross!value added
GZMP	generalized!ZMP

H

H	helical joint
HAL	hybrid!assistive limb
HAMMER	hierarchical!attentive multiple models for execution and recognition
HASY	hand!arm system
HBBA	hybrid behavior-based architecture
HCI	human–computer interaction

HD	high definition
HD	haptic device
HD-SDI	high-definition serial digital interface
HDSL	high data rate digital subscriber line
HE	hand!exoskeleton
HF	hard finger
HF	histogram filter
HFAC	high frequency alternating current
HHMM	hierarchical!hidden Markov model
HIC	head injury criterion
HIII	Hybrid III dummy
HIP	haptic interaction point
HJB	Hamilton–Jacobi–Bellman
HJI	Hamilton–Jacobi–Isaac
HMCS	human–machine!cooperative system
HMD	head-mounted display
HMDS	hexamethyldisilazane
HMI	human–machine!interaction
HMI	human–machine!interface
HMM	hidden Markov model
HO	human operator
HOG	histogram of oriented gradient
HOG	histogram of oriented features
HPC	high-performance computing
HRI	human–robot interaction
HRI/OS	HRI operating system
HRP	humanoid robotics project
HRR	high resolution radar
HRTEM	high-resolution transmission electron microscope
HSGR	high safety goal
HST	Hubble space telescope
HSTAMIDS	handheld standoff mine detection system
HSWR	high safety wide region
HTAS	high tech automotive system
HTML	hypertext markup language
HTN	hierarchical task network
HTTP	hypertext transmission protocol
HW/SW	hardware/software

I

I/O	input/output
I3CON	industrialized, integrated, intelligent, construction
IA	interval algebra
IA	instantaneous!allocation
IAA	interaction!agent
IAB	International Association of Bioethics
IACAP	International Association for Computing and Philosophy
IAD	interaural amplitude difference
IAD	intelligent!assisting device
IARC	International Aerial Robotics Competition
IAS	intelligent!autonomous system
IBVS	image-based visual servo control
IC	integrated chip
IC	integrated circuit
ICA	independent!component analysis
ICAPS	International Conference on Automated Planning and Scheduling
ICAR	International Conference on Advanced Robotics
ICBL	International Campaign to Ban Landmines
ICC	instantaneous center of curvature
ICE	internet communications engine
ICP	iterative closest point
ICR	instantaneous center of rotation
ICRA	International Conference on Robotics and Automation
ICT	information!and communication technology
ID	inside diameter
ID	identifier
IDE	integrated!development environment
IDL	interface definition language
IE	information!ethics
IED	improvised explosive device
IEEE	Institute of Electrical and Electronics Engineers
IEKF	iterated extended Kalman filter
IETF	internet!engineering task force
IFA	Internationale Funk Ausstellung
IFOG	interferometric fiber-optic gyro
IFR	International Federation of Robotics
IFREMER	Institut français de recherche pour l'exploitation de la mer
IFRR	International Foundation of Robotics Research
IFSAR	interferometric SAR
IHIP	intermediate haptic interaction point
IIR	infinite impulse response
IIS	Internet Information Services
IIT	Istituto Italiano di Tecnologia
IJCAI	International Joint Conference on Artificial Intelligence
IK	inverse kinematics
ILLS	instrumented logical sensor system
ILO	International Labor Organization
ILQR	iterative linear quadratic regulator
IM	injury measure
IMAV	International Micro Air Vehicles
IMTS	intelligent!multimode transit system
IMU	inertial measurement unit
INS	inertia navigation system

INS	inertial navigation system
IO	input output
IO	inferior olive
IOSS	input-output-to-state stability
IP	internet protocol
IP	interphalangeal
IPA	Institute for Manufacturing Engineering and Automation
IPC	interprocess communication
IPC	international AI planning competition
IPMC	ionic polymer-metal composite
IPR	intellectual property right
IR	infrared
IRB	Institutional Review Board
IREDES	International Rock Excavation Data Exchange Standard
IRL	in real life
IRL	inverse!reinforcement learning
IRLS	iteratively reweighted least square
IRNSS	Indian regional navigational satellite system
IROS	Intelligent Robots and Systems
IS	importance sampling
ISA	industrial standard architecture
ISA	international standard atmosphere
ISAR	inverse SAR
ISDN	integrated services digital network
ISE	international submarine engineering
ISER	International Symposium on Experimental Robotics
ISM	implicit shape model
ISO	International Organization for Standardization
ISP	Internet service provider
ISR	intelligence, surveillance and reconnaissance
ISRR	International Symposium of Robotics Research
ISS	international space station
ISS	input-to-state stability
IST	Instituto Superior Técnico
IST	Information Society Technologies
IT	intrinsic tactile
IT	information!technology
IT	inferotemporal cortex
ITD	interaural time difference
IU	interaction!unit
IV	instrumental variable
IvP	interval programming
IWS	intelligent!wheelchair system
IxTeT	indexed time table

J

JAEA	Japan Atomic Energy Agency
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JAMSTEC	Japan Marine Science and Technology Center
JAUS	joint architecture for unmanned systems
JAXA	Japan Aerospace Exploration Agency
JDL	joint directors of laboratories
JEM	Japan Experiment Module
JEMRMS	Japanese experiment module remote manipulator system
JHU	Johns Hopkins University
JND	just noticeable difference
JPL	Jet Propulsion Laboratory
JPS	jigsaw positioning system
JSC	Johnson Space Center
JSIM	joint-space inertia matrix
JSP	Java server pages

K

KAIST	Korea Advanced Institute of Science and Technology
KERS	kinetic energy recovery system
KIPR	KISS Institute for Practical Robotics
KLD	Kullback–Leibler divergence
KNN	k-nearest neighbor
KR	knowledge representation
KRISO	Korea Research Institute of Ships and Ocean Engineering

L

L/D	lift-to-drag
LAAS	Laboratory for Analysis and Architecture of Systems
LADAR	laser radar
LAGR	learning!applied to ground robots
LARC	Lie algebra rank condition
LARS	Laparoscopic Assistant Robotic System
LASC	Longwall Automation Steering Committee
LBL	long-baseline system
LCAUV	long-range cruising AUV
LCC	life-cycle-costing
LCD	liquid-crystal display
LCM	light-weight communications and marshalling
LCP	linear complementarity problem
LCSP	linear constraint satisfaction program
LDA	latent Dirichlet allocation
LED	light-emitting diode
LENAR	lower!extremity nonanthropomorphic robot

LEO	low!Earth orbit
LEV	leading edge vortex
LfD	learning!from demonstration
LGN	lateral!geniculate nucleus
LHD	load!haul-dump
LIDAR	light detection and ranging
LIGA	Lithographie, Galvanoumformung, Abformung
LIP	linear inverted pendulum
LIP	lateral!intraparietal sulcus
LiPo	lithium polymer
LLC	locality constrained linear coding
LMedS	least median of squares
LMS	laser measurement system
LOG	Laplacian of Gaussian
LOPES	lower!extremity powered exoskeleton
LOS	line-of-sight
LP	linear program
LQG	linear quadratic Gaussian
LQR	linear quadratic regulator
LSS	logical sensor system
LSVM	latent support vector machine
LtA	lighter-than-air
LtA-UAS	lighter-than-air system
LTL	linear temporal logic
LVDT	linear variable differential transformer
LWR	light-weight robot

M

MACA	Afghanistan Mine Action Center
MACCEPA	mechanically adjustable compliance and controllable equilibrium position actuator
MAP	maximum a posteriori
MARS	multiappendage robotic system
MARUM	Zentrum für Marine Umweltwissenschaften
MASE	Marine Autonomous Systems Engineering
MASINT	measurement!and signatures intelligence
MAV	micro aerial vehicles
MAZE	Micro robot maze contest
MBA	motivated behavioral architecture
MBARI	Monterey Bay Aquarium Research Institute
MBE	molecular-beam epitaxy
MBS	mobile!base system
MC	Monte Carlo
MCFC	molten carbonate fuel cell
MCP	magazining, cleaning, plotting
MCP	metacarpophalangeal
MCS	mission!control system
MDARS	mobile!detection assessment and response system
MDL	minimum description length
MDP	Markov decision process
ME	mechanical!engeneering
MEG	magnetoencephalography
MEL	Mechanical Engineering Laboratory
MEMS	microelectromechanical system
MEP	motor!evoked potential
MESSIE	multi expert system for scene interpretation and evaluation
MESUR	Mars environmental survey
MF	mossy fiber
MFI	micromechanical flying insect
MFSK	multiple FSK
MHS	International Symposium on Micro Mechatronics and Human Science
MHT	multihypothesis tracking
MIA	mechanical impedance adjuster
MIME	mirror!image movement enhancer
MIMICS	multimodal immersive motion rehabilitation with interactive cognitive system
MIMO	multiple-input–multiple-output
MIP	medial intraparietal sulcus
MIPS	microprocessor without interlocked pipeline stages
MIR	mode identification and recovery
MIRO	middleware for robot
MIS	minimally invasive surgery
MIT	Massachusetts Institute of Technology
MITI	Ministry of International Trade and Industry
MKL	multiple kernel learning
ML	machine!learning
MLE	maximum likelihood estimate
MLR	mesencephalic locomotor region
MLS	multilevel surface map
MMC	metal matrix composite
MMMS	multiple master multiple-slave
MMSAE	multiple model switching adaptive estimator
MMSE	minimum mean-square error
MMSS	multiple master single-slave
MNS	mirror!neuron system
MOCVD	metallo-organic chemical vapor deposition
MOMR	multiple operator multiple robot
MOOS	mission oriented operating suite
MOOS	motion-oriented operating system
MORO	mobile robot
MOSR	multiple operator single robot
MP	moving plate
MPC	model predictive control

MPF manifold particle filter
MPFIM multiple!paired forward-inverse model
MPHE multiphalanx hand exoskeleton
MPSK Mary phase shift keying
MQAM Mary quadrature amplitude modulation
MR magnetorheological
MR multiple reflection
MR multirobot!task
MRAC model reference adaptive control
MRDS Microsoft robotics developers studio
MRF Markov random field
MRHA multiple!resource host architecture
MRI magnetic resonance imaging
MRSR Mars rover sample return
MRTA multirobot!task allocation
MSAS multifunctional satellite augmentation system
MSER maximally stable extremal region
MSHA US Mine Safety and Health Administration
MSK minimum shift keying
MSL middle-size league
MSM master–slave!manipulator
MST microsystem technology
MT momentum theory
MT multitask
MT medial temporal area
MTBF mean time between failures
MTI moving target indicator
MVERT move value estimation for robot teams
MWNT multiwalled carbon nanotube

N

N&G nursery and greenhouse
NAP nonaccidental property
NASA National Aeronautics and Space Agency
NASDA National Space Development Agency of Japan
NASREM NASA/NBS standard reference model
NBS National Bureau of Standards
NC numerical control
ND nearness diagram navigation
NDDS network data distribution service
NDGPS nationwide different GPS system
NDI nonlinear dynamic inversion
NDT normal distributions transform
NEMO network!mobility
NEMS nanoelectromechanical system
NEO neodymium
NERVE New England Robotics Validation and Experimentation
NESM normalized ESM
NIDRR National Institute on Disability and Rehabilitation Research
NiMH nickel metal hydride battery
NIMS networked!infomechanical systems
NIOSH United States National Institute for Occupational Safety and Health
NIRS near infrared spectroscopy
NIST National Institute of Standards and Technology
NLIS national livestock identification scheme
NLP nonlinear!programming problem
NMEA National Marine Electronics Association
NMF nonnegative matrix factorization
NMMI natural machine motion initiative
NMR nuclear!magnetic resonance
NN neural network
NOAA National Oceanic and Atmospheric Administration
NOAH navigation!and obstacle avoidance help
NOC National Oceanography Centre
NOTES natural!orifice transluminal surgery
NPO nonprofit organization
NPS Naval Postgraduate School
NQE national qualifying event
NRI national robotics initiative
NRM nanorobotic manipulator
NRTK network real-time kinematic
NTPP nontangential proper part
NTSC National Television System Committee
NURBS nonuniform rational B-spline
NUWC Naval Undersea Warfare Center Division Newport
NZDF New Zealand Defence Force

O

OAA open!agent architecture
OASIS onboard autonomous science investigation system
OAT optimal arbitrary time-delay
OBU on board unit
OC optimal control
OCPP optimal!coverage path planning
OCR OC robotics
OCT optical!coherence tomography
OCU operator control unit
OD outer diameter
ODE ordinary differential equation
ODE open dynamics engine
ODI ordinary differential inclusion
OECD Organization for Economic Cooperation and Development
OKR optokinetic response
OLP offline programming

OM	optical microscope
OM	occupancy map
ONR	US Office of Naval Research
OOF	out of field
OOTL	human!out of the loop control
OPRoS	open platform for robotic service
ORCA	open robot control architecture
ORCCAD	open robot controller computer aided design
ORI	open!roboethics initiative
ORM	obstacle restriction method
OROCOS	open robot control software
ORU	orbital replacement unit
OS	operating system
OSC	operational-space control
OSIM	operational-space inertia matrix
OSU	Ohio State University
OTH	over-the-horizon
OUR-K	ontology based unified robot knowledge
OWL	web ontology language
OxIM	Oxford intelligent machine

P

P	prismatic joint
P&O	prosthetics!and orthotic
PA	point algebra
PACT	perception!for action control theory
PAD	pleasure arousal dominance
PAFC	phosphoric acid fuel cell
PAM	pneumatic artificial muscle
PaMini	pattern-based mixed-initiative
PANi	polyaniline
PANTOMEC	pantograph mechanism driven
PAPA	privacy, accuracy, intellectual property, and access
PAS	pseudo-amplitude scan
PAT	proximity!awareness technology
PB	parametric!bias
PbD	programming!by demonstration
PBVS	pose-based visual servo control
PC	polycarbonate
PC	personal computer
PC	principal contact
PC	passivity controller
PC	proprioception
PC	Purkinje cell
PCA	principal component analysis
PCI	peripheral component interconnect
PCIe	peripheral component interconnect express
PCL	point cloud library
PCM	programmable!construction machine
PD	proportional–derivative
PDE	partial differential equation
PDGF	power!data grapple fixture
PDMS	polydimethylsiloxane
PDOP	positional dilution of precision
PDT	proximity!detection technology
PEAS	probing environment and adaptive sleeping protocol
PEFC	polymer electrolyte fuel cell
PEMFC	proton exchange membrane fuel cell
PerceptOR	perception!for off-road robotics
PET	positron emission tomography
PF	particle filter
PF	parallel!fiber
PFC	prefrontal cortex
PFH	point feature histogram
PFM	potential field method
PGM	probabilistic graphical model
PGRL	policy gradient!reinforcement learning
pHRI	physical!human–robot interaction
PI	policy iteration
PI	possible!injury
PI	propositional integral
PI	proportional–integral
PIC	programmable!intelligent computer
PID	proportional–integral–derivative
PIT	posterior!inferotemporal cortex
PKM	parallel kinematics machine
PKM	parallel kinematic machine
PL	power loading
PLC	programmable!logic controller
PLD	programmable!logic device
PLEXIL	plan execution interchange language
PLSA	probabilistic latent semantic analysis
PLZT	lead lanthanum zirconate titanate
PM	permanent magnet
PMC	polymer matrix composite
PMMA	polymethyl methacrylate
PneuNet	pneumatic network
PnP	prespective-n-point
PNT	Petri net transducer
PO	partially overlapping
PO	passivity observer
POE	local product-of-exponential
POI	point!of interest
POM	polyoxymethylene
POMDP	partially observable Markov decision process
POP	partial-order planning
PPS	precise positioning system
PPy	polypyrrole
PR	positive photoresist
PRM	probabilistic roadmap
PRM	probabilistic roadmap method
PRN	pseudo-random noise

PRoP	personal roving presence
ProVAR	professional vocational assistive robot
PRS	procedural reasoning system
PS	power source
PSD	position sensing device
PSD	position-sensitive-device
PSK	phase shift keying
PSPM	passive set-position modulation
PTAM	parallel tracking and mapping
PTU	pan–tilt unit
PUMA	programmable!universal machine for assembly
PVA	position, velocity, and attitude
PVC	polyvinyl chloride
PVD	physical vapor deposition
PVDF	polyvinylidene fluoride
PWM	pulse-width modulation
PwoF	point-contact-without-friction
PZT	lead zirconate titanate

Q

QAM	quadrature amplitude modulation
QD	quantum dot
QID	qualifier, inspection and demonstration
QOLT	quality!of life technology
QOS	quality of service
QP	quadratic programming
QPSK	quadrature phase shift keying
QRIO	quest for curiosity
QSC	quasistatic!constrained
QT	quasistatic telerobotics
QZSS	quasi-zenith satellite system

R

R	revolute joint
R.U.R.	Rossum's Universal Robots
RA	rectangle algebra
RAC	Robotics and Automation Council
RAIM	receiver autonomous integrity monitor
RALF	robotic arm large and flexible
RALPH	rapidly adapting lane position handler
RAM	random!access memory
RAMS	robot-assisted microsurgery
RAMS	random!access memory system
RANSAC	random sample consensus
RAP	reactive action package
RAS	Robotics and Automation Society
RBC	recognition!by-component
RBF	radial!basis function network
RBF	radial!basis function
RBT	robot!experiment
RC	radio control
RC	robot!controller
RCC	region connection calculus
RCC	remote center of compliance
RCM	remote!center of motion
RCP	rover chassis prototype
RCR	responsible conduct of research
RCS	real-time control system
RCS	rig control system
RDT	rapidly exploring dense tree
RECS	robotic!explosive charging system
REINFORCE	reward increment = nonnegative factor × offset reinforcement × characteristic eligibility
RERC	Rehabilitation Engineering Research Center
RF	radio frequency
RFID	radio frequency identification
RG	rate gyro
RGB-D	color camera with depth
RGB-D	red green blue distance
RGB-D	red–green–blue–depth
RHIB	rigid!hull inflatable boat
RIE	reactive-ion etching
RIG	rate-integrating gyro
RISC	reduced instruction set computer
RL	reinforcement learning
RLG	ring laser gyroscope
RLG	random loop generator
RMC	resolved momentum control
RMDP	relational Markov decision processes
RMMS	reconfigurable modular manipulator system
RMS	root mean square
RNDF	route network definition file
RNEA	recursive Newton–Euler algorithm
RNN	recurrent neural network
RNNPB	recurrent neural network with parametric bias
RNS	reaction!null-space
ROC	receiver operating curve
ROC	remote!operations centre
ROCCO	robot!construction system for computer integrated construction
ROD	robot!oriented design
ROKVISS	robotics component verification on ISS
ROKVISS	robotics!components verification on the ISS
ROM	run-of-mine
ROM	read-only memory
ROMAN	Robot and Human Interactive Communication
ROS	robot operating system
ROV	remotely operated vehicle
ROV	remotely!operated underwater vehicle

RP	rapid prototyping
RP-VITA	remote presence virtual + independent telemedicine assistant
RPC	remote procedure call
RPI	Rensselaer Polytechnic Institute
RPS	room positioning system
RRSD	Robotics and Remote Systems Division
RRT	rapidly exploring random tree
RS	Reeds and Shepp
RSJ	Robotics Society of Japan
RSS	Robotics Science and Systems
RSTA	reconnaissance, surveillance, and target acquisition
RSU	road!side unit
RT	real-time
RT	room temperature
RT	reaction!time
RTCMS C104	Radio Technical Commission for Maritime Services Special Committee 104
RTD	resistance temperature devices
RTI	real-time innovation
RTK	real-time kinematics
rTMS	repetitive!TMS
RTS	real-time system
RTT	real-time toolkit
RV	rotary vector
RVD	rendezvous/docking
RW	rotary-wing
RWI	real-world interface
RWS	robotic workstation
R&D	research and development
R&D	research and development

S

SA	simulated annealing
SA	selective availability
SAFMC	Singapore Amazing Flying Machine Competition
SAI	simulation!and active interfaces
SAM	smoothing and mapping
SAN	semiautonomous navigation
SAR	synthetic aperture radar
SAR	socially assistive robotics
SARSA	state action-reward-state-action
SAS	synthetic aperture sonar
SAS	stability augmentation system
SAT	International Conference on Theory and Applications of Satisfiability Testing
SBAS	satellite-based augmentation system
SBL	short baseline
SBSS	space based space surveillance
SC	sparse coding
SCARA	selective compliance assembly robot arm
SCI	spinal cord!injury
sci-fi	science fiction
SCM	smart composite microstructures
SCM	soil!contact model
SD	standard deviation
SDK	standard development kit
SDK	software development kit
SDM	shape deposition manufacturing
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 microscope
SET	single electron transistor
SF	soft finger
SFM	structure from motion
SFX	sensor fusion effect
SGAS	semiglobal asymptotic stability
SGD	stochastic gradient descent
SGM	semiglobal!matching
SGUUB	semiglobal uniform ultimate boundedness
SIFT	scale-invariant feature transform
SIGINT	signal!intelligence
SIR	sampling importance resampling
SISO	single input single-output
SKM	serial!kinematic machines
SLA	stereolithography
SLAM	simultaneous localization and mapping
SLICE	specification language for ICE
SLIP	spring loaded inverted pendulum
SLRV	surveyor lunar rover vehicle
SLS	selective laser sintering
SM	static margin
SMA	shape memory alloy
SMAS	solid material assembly system
SMC	sequential Monte Carlo
SME	small!and medium enterprises
SMMS	single-master multiple-slave
SMP	shape memory polymer
SMS	short message service
SMSS	single-master single-slave
SMT	satisfiabiliy modulo theory
SMU	safe!motion unit
SNAME	society of naval architects and marine engineer
SNOM	scanning near-field optical microscopy
SNR	signal-to-noise ratio
SNS	spallation neutron source
SOFC	solid oxide fuel cell
SOI	silicon-on-insulator

SOMA	stream-oriented messaging architecture
SOMR	single operator multiple robot
SOS	save our souls
SOSR	single operator single robot
SPA	sense-plan-act
SPaT	signal!phase and timing
SPAWAR	Space and Naval Warfare Systems Center
SPC	self-posture changeability
SPDM	special purpose dexterous manipulator
SPHE	single-phalanx hand exoskeleton
SPL	single!port laparoscopy
SPL	standard!platform
SPM	scanning probe microscope
SPM	spatial pyramid matching
SPMS	shearer position measurement system
SPS	standard position system
SPU	spherical, prismatic, universal
SQP	sequential!quadratic programming
SR	single-robot task
SRA	spatial!reasoning agent
SRCC	spatial remote center compliance
SRI	Stanford Research Institute
SRMS	shuttle remote manipulator system
SSA	sparse surface adjustment
SSC	smart soft composite
SSL	small-size league
SSRMS	space!station remote manipulator system
ST	single-task
STEM	science, technology, engineering and mathematics
STM	scanning tunneling microscope
STP	simple temporal problem
STriDER	self-excited tripodal dynamic experimental robot
STS	superior!temporal sulcus
SUGV	small!unmanned ground vehicle
SUN	scene understanding
SURF	robust feature
SVD	singular value decomposition
SVM	support vector machine
SVR	support vector regression
SWNT	single-walled carbon nanotube
SWRI	Southwest Research Institute

T

T-REX	teleo-reactive executive
TA	time-extended assignment
TAL	temporal action logic
TAM	taxon!affordance model
TAP	test action pair
TBG	time-base generator
TC	technical committee
TCFFHRC	Trinity College's Firefighting Robot Contest
TCP	transfer control protocol
TCP	tool center point
TCP	transmission control protocol
TCSP	temporal constraint satisfaction problem
tDCS	transcranial!direct current stimulation
TDL	task description language
TDT	tension-differential type
TECS	total energy control system
TEM	transmission electron microscope
tEODor	telerob explosive ordnance disposal and observation robot
TFP	total!factor productivity
TL	temporal logic
TMM	transfer matrix method
TMS	tether management system
TMS	transcranial!magnetic stimulation
TNT	trinitrotoluene
TOA	time of arrival
TOF	time-of-flight
ToF	time-of-flight
TORO	torque!controlled humanoid robot
TPaD	tactile pattern display
TPBVP	two-point boundary value problem
TPP	tangential proper part
TRC	Transportation Research Center
TRIC	task space retrieval using inverse optimal control
TS	technical!specification
TSEE	teleoperated!small emplacement excavator
TSP	telesensor programming
TTC	time-to-collision
TUM	Technical University of Munich
TV	television

U

U	universal joint
UAS	unmanned aircraft system
UAS	unmanned!aerial system
UAV	unmanned aerial vehicle
UAV	fusing air vehicle
UAV	fielded unmanned aerial vehicle
UB	University of Bologna
UBC	University of British Columbia
UBM	Universität der Bundeswehr Munich
UCLA	University of California, Los Angeles
UCO	uniformly completely observable
UDP	user datagram protocol
UDP	user data protocol
UGV	unmanned!ground vehicle
UHD	ultrahigh definition

UHF	ultrahigh frequency
UHV	ultrahigh-vacuum
UKF	unscented Kalman filter
ULE	upper!limb exoskeleton
UML	unified modeling language
UMV	unmanned marine vehicle
UNESCO	United Nations Educational, Scientific and Cultural Organization
UPnP	universal plug and play
URC	Ubiquitous Robotic Companion
URL	uniform resource locator
USAR	urban!search and rescue
USB	universal!serial bus
USBL	ultrashort baseline
USBL	ultrashort-baseline
USC	University of Southern California
USV	unmanned!surface vehicle
UTC	universal coordinated time
UUB	uniform ultimate boundedness
UUV	unmanned underwater vehicle
UV	ultraviolet
UVMS	underwater vehicle!manipulator system
UWB	ultrawide band
UXO	unexploded ordnance

V

V2V	vehicle-to-vehicle
VAS	visual!analog scale
VCR	video!cassette recorder
vdW	van der Waals
VE	virtual environment
VFH	vector field histogram
VHF	very high frequency
VI	value iteration
VIA	variable impedance actuator
VIP	ventral intraparietal
VM	virtual!manipulator
VME	Versa Module Europa
VO	virtual object
VO	velocity obstacle
VOC	visual object class
VOR	vestibular-ocular reflex
VR	variable reluctance
VRML	virtual reality modeling language
VS	visual servo
VS-Joint	variable stiffness joint
VSA	variable stiffness actuator
VTOL	vertical take-off and landing

W

W3C	WWW consortium
WAAS	wide-area augmentation system
WABIAN	Waseda bipedal humanoid
WABOT	Waseda robot
WAM	whole-arm manipulator
WAN	wide-area network
WASP	wireless!ad-hoc system for positioning
WAVE	wireless!access in vehicular environments
WCF	worst-case factor
WCR	worst-case range
WDVI	weighted!difference vegetation index
WG	world!graph
WGS	World Geodetic System
WHOI	Woods Hole Oceanographic Institution
WML	wireless markup language
WMR	wheeled mobile robot
WSN	wireless!sensor network
WTA	winner-take-all
WTC	World Trade Center
WWW	world wide web

X

XCOM	extrapolated center of mass
XHTML	extensible hyper text markup language
XML	extensible markup language
xUCE	urban!challenge event

Y

YARP	yet another robot platform

Z

ZMP	zero moment point
ZOH	zero order hold
ZP	zona pellucida