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of Robotics

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Springer Handbook
of Robotics

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2nd Edition
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.

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.

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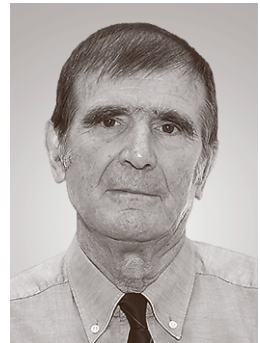
For the last decade of the millennium, robotics largely dealt with the intelligent robot paradigm, blending together robots and machine-intelligence generic research within themes covering advanced sensing and perception, task reasoning and planning, operational and decisional autonomy, functional integration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

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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 lev-

els. 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.

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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
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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.
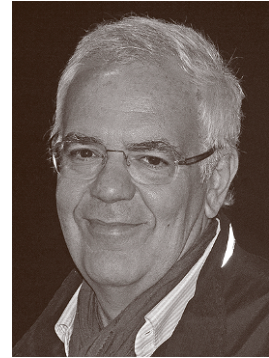
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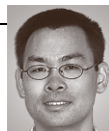
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