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# **Springer Handbook of Robotics**

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# Springer Handbook of Robotics

Bruno Siciliano, Oussama Khatib (Eds.)

With DVD-ROM, 953 Figures, 422 in four color and 84 Tables



Springer

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Editors:

Professor Bruno Siciliano  
PRISMA Lab  
Dipartimento di Informatica e Sistemistica  
Università degli Studi di Napoli Federico II  
Via Claudio 21, 80125 Napoli, Italy  
siciliano@unina.it

Professor Oussama Khatib  
Artificial Intelligence Laboratory  
Department of Computer Science  
Stanford University  
Stanford, CA 94305-9010, USA  
khatib@cs.stanford.edu

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## Foreword

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

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

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

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

There were also a few mechanical devices developed as hand, leg, and arm prosthetics, and, a bit later, some

exoskeletal devices to enhance human performance. In those days there were no microprocessors. So, these devices were either without computer control, or tethered to a remote so-called minicomputer, or even a mainframe computer.

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

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

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

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



**Bernard Roth**  
Professor of Mechanical  
Engineering  
Stanford University

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

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

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

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

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

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

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

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

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

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

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

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

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

The first regular series of conferences emphasizing research, rather than the industrial, aspects of robotics, was inaugurated in 1973. It was sponsored jointly by the International Center for Mechanical Sciences (CISM), based in Udine, Italy, and the International Federation for the Theory of Mechanisms and Machines (IFTToMM). (Although IFTToMM 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



**Georges Giralt**

Emeritus Research Director  
LAAS-CNRS Toulouse

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

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

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

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

Hence robotics researches could bring together these two different branches, with intelligent robots categorized in a solely computational way as bounded

rationality machines, expanding on the 1980s third-generation robot definition:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The concept of the personal robot, expanding to robot assistant and universal companion, is a truly great challenge for robotics as a scientific and technical field,

offering the mid/long-term perspective of achieving a paramount societal and economical impact. This introduces, and questions, front-line topics encompassing cognitive aspects: user-tunable human-machine intelligent interfaces, perception (scene analysis, category identification), open-ended learning (understanding the universe of action), skills acquisition, extensive robot-world data processing, decisional autonomy, and dependability (safety, reliability, communication, and operating robustness).

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

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

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

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

Toulouse, December 2007

Georges Giralt

## Foreword



**Hirochika Inoue**

Professor Emeritus  
The University of Tokyo

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

In its infancy, the core of robotics consisted of pattern recognition, automatic control, and artificial intelligence. Taking on these

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

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

As robotics entered its adolescence, researchers were ambitious to explore new horizons. Kinematics, dynamics, and control system theory were refined and applied to real complex robot mechanisms. To plan and carry

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

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

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

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

Since my initial research to make a robot turn a crank, four decades have passed. I feel both lucky and happy to have witnessed the growth of robotics from its early beginnings. To give birth to robotics, fundamental technologies were imported from other disciplines. Neither textbooks nor handbooks were available. To reach the present stage, a great many scientists and engineers have challenged new frontiers; advancing robotics, they have enriched this body of knowledge from a variety of perspectives. The fruits of their endeavors are compiled in this *Handbook of Robotics*. More than 100 of

the world's leading experts have collaborated in producing this publication. Now, people who wish to commit themselves to robotics research can find a firm foundation to build upon. This Handbook is sure to be used to further advance robotics science, reinforce engineering education, and systematically compile knowledge that will innovate both society and industry.

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

Tokyo, September 2007

Hirochika Inoue

## Foreword



**Rodney Brooks**

Panasonic Professor  
of Robotics  
Massachusetts Institute  
of Technology

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

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

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

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

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

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

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

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

Each of these is a very difficult goal. However even small amounts of progress towards any one of these goals

will have immediate applications to robots out in the world. Good reading and best wishes as you contribute further to robotkind.

Cambridge, October 2007

Rodney Brooks



## Preface

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

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

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

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

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

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

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

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

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

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



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

We are deeply thankful to the authors for their intellectual contributions, as well as to the reviewers and part editors for their conscientious work. We are indebted to Werner Skolaut, the Senior Manager of Springer Handbooks in Science and Engineering, who soon became a devoted member of our team with his painstaking support to technically editing the authors' typescripts and linking the editors' work with the copy editing and production of the handbook. We also wish to acknowledge the highly professional work by the Le-T<sub>E</sub>X staff, which re-typeset all the text, redrew and improved the many

illustrations, while timely interacting with the authors during the proof-reading of the material.

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

Napoli and Stanford  
April 2008

Bruno Siciliano  
Oussama Khatib

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## About the Editors

**Bruno Siciliano** received his Doctorate degree in Electronic Engineering from the University of Naples in 1987. He is Professor of Control and Robotics, and Director of the **PRISMA** Lab in the Department of Computer and Systems Engineering at University of Naples. His current research is in force control, visual servoing, dual-arm/hand manipulation, lightweight flexible arms, human-robot interaction and service robotics. Professor Siciliano has co-authored 6 books and 5 edited volumes, 65 journal papers, 165 conference papers and book chapters, and has delivered 85 invited lectures and seminars at institutions around the world. He is Co-Editor of the Springer Tracts in Advanced Robotics (STAR) series, the Springer Handbook of Robotics, and has served on the Editorial Boards of prestigious journals, as well as Chair or Co-Chair for numerous international conferences. He is a Fellow of both **IEEE** and **ASME**. Professor Siciliano is the President of the **IEEE** Robotics and Automation Society (**RAS**), after serving as Vice President for Technical Activities and Vice President for Publications, as a Distinguished Lecturer, as a member of the Administrative Committee and of several other society committees.



**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 current research, which focuses on human-centered robotics, is concerned with human motion synthesis, humanoid robotics, haptic teleoperation, medical robotics, and human-friendly robot design. His research in these areas builds on a large body of studies he pursued over the past 25 years and published in over 200 contributions. Professor Khatib has delivered over 50 keynote presentations and several hundreds of colloquia and seminars at institutions around the world. He is Co-Editor of the STAR series, the Springer Handbook of Robotics, and has served on the Advisory and Editorial Boards of prestigious institutions and journals, as well as Chair or Co-Chair for numerous international conferences. He is a Fellow of **IEEE** and has served **RAS** as a Distinguished Lecturer and as a member of the Administrative Committee. Professor Khatib is the President of the International Foundation of Robotics Research (**IFRR**) and a recipient of the Japan Robot Association (JARA) Award in Research and Development.





## About the Part Editors



David E. Orin

The Ohio State University  
Department of Electrical Engineering  
Columbus, OH, USA  
[orin.1@osu.edu](mailto:orin.1@osu.edu)

### Part A

David E. Orin received his PhD degree in Electrical Engineering from The Ohio State University in 1976. From 1976 to 1980 he taught at Case Western Reserve University. Since 1981, he has been at The Ohio State University, where he is currently a Professor of Electrical and Computer Engineering. His current work focuses on dynamic movement in biped locomotion. He has made many contributions to robot dynamics and legged locomotion, and he has over 125 publications. He has received a number of educational awards from his institution. He is an IEEE Fellow and has served on the program committee for several international conferences. He has received the Distinguished Service Award in recognition of his service for the IEEE Robotics and Automation Society, such as Vice President for Finance, Secretary, member of the Administrative Committee, and co-chair of the Fellow Evaluation Committee.

Frank C. Park

Seoul National University  
Mechanical and Aerospace Engineering  
Seoul, Korea  
[fcp@snu.ac.kr](mailto:fcp@snu.ac.kr)



### Part B

Frank C. Park received the PhD degree in Applied Mathematics from Harvard University in 1991. From 1991 to 1995 he was an Assistant Professor of Mechanical and Aerospace Engineering at the University of California, Irvine. Since 1995 he has been at the School of Mechanical and Aerospace Engineering at Seoul National University, where he is currently full professor. His primary research interests in robotics include robot mechanics, planning, and control, robot design and structures, and industrial robotics. His other research interests include nonlinear systems theory, differential geometry and its applications, and related areas of applied mathematics. He has served the IEEE Robotics and Automation Society as a Secretary and as a Senior Editor of the IEEE Transactions on Robotics.

Henrik I. Christensen

Georgia Institute of Technology  
Robotics and Intelligent Machines @ GT  
Atlanta, GA, USA  
[hic@cc.gatech.edu](mailto:hic@cc.gatech.edu)



### Part C

Henrik I. Christensen is the KUKA Chair of Robotics and Director of Robotics at Georgia Institute of Technology, Atlanta, GA. He received the MS and PhD degrees from Aalborg University in 1987 and 1990, respectively. He has held positions in Denmark, Sweden, and USA. He has published more than 250 contributions across vision, robotics, and AI. Results from his research have been commercialized through a number of major companies and 4 spin-offs. He served as the founding coordinator of the European Robotics Research Network (EURON). He has participated as a senior organizer in more than 50 different conferences and workshops. He is a Fellow of the International Foundation of Robotics Research, an Editorial Board member of the STAR series, and has served on the editorial board of several leading journals in the field. He has been a Distinguished Lecturer of the IEEE Robotics and Automation Society.



**Makoto Kaneko**

Osaka University  
Department of Mechanical Engineering  
Graduate School of Engineering  
Suita, Japan  
*mk@mech.eng.osaka-u.ac.jp*

**Part D**

Makoto Kaneko received the MS and PhD degrees in Mechanical Engineering from Tokyo University in 1978 and 1981, respectively. From 1981 to 1990 he was Researcher at the Mechanical Engineering Laboratory, from 1990 to 1993 an Associate Professor at Kyushu Institute of Technology, from 1993 to 2006 Professor at Hiroshima University, and in 2006 became a Professor at Osaka University. His research interests include tactile-based active sensing, grasping strategy, hyper human technology and its application to medical diagnosis, and his work has received 17 awards. He is an Editorial Board member of the STAR series and has served as chair or co-chair for several international conferences. He is an IEEE Fellow. He has served the IEEE Robotics and Automation Society as a Vice-President for Member Activities and as a Technical Editor of the IEEE Transactions on Robotics and Automation.



**Raja Chatila**

LAAS-CNRS  
Toulouse, France  
*raja.chatila@laas.fr*

**Part E**

Raja Chatila received his PhD degree from the University of Toulouse in 1981. He is currently Director of LAAS-CNRS (Laboratory of Systems Analysis and Architecture), Toulouse, France where he is since 1983. He was an invited professor at Tsukuba University in 1997. His research work encompasses several aspects in field, planetary, aerial and service robotics, cognitive robotics, learning, human-robot interaction, and networked robotics. He is author of over 150 international publications on these topics. He is a Fellow of the International Foundation of Robotics Research. He has served on the editorial boards of several leading publications, including the STAR series, and as chair or co-chair for several international conferences. He has served the IEEE Robotics and Automation Society as a member of the Administrative Committee, as an Associate Editor of the IEEE Transactions on Robotics and Automation and as a Distinguished Lecturer. He is a member of IEEE, ACM and AAAI, and a member of various national and international boards and evaluation committees.

**Alexander Zelinsky**

Commonwealth Scientific and Industrial  
Research Organisation (CSIRO)  
ICT Centre  
Epping, NSW, Australia  
*alex.zelinsky@csiro.au*



**Part F**

Alexander Zelinsky is the Director of the Information and Communication Technologies Centre at the CSIRO. Before joining CSIRO, he was CEO and Founder of Seeing Machines Pty Limited and a Professor at the Australian National University, in the Research School of Information Sciences and Engineering. He is a well-known scientist specializing in robotics and computer vision, he is widely recognized as an innovator in human-machine interaction, and he has over 100 publications in the field. His work has received both national and international awards. He has served on the editorial boards of two leading publications, and on the program committees of several international conferences. He is an IEEE Fellow and has served the IEEE Robotics and Automation Society as a member of the Administrative Committee and as Vice-President for Industrial Activities.

**Daniela Rus**

Massachusetts Institute of Technology  
CSAIL Center for Robotics  
Cambridge, MA, USA  
*rus@csail.mit.edu*



**Part G**

Daniela Rus received her PhD degree in Computer Science from Cornell University in 1992. From 1994 to 2003 she taught at Dartmouth, Hanover. Since 2004 she has been at MIT, where she is currently a Professor of Electrical Engineering and Computer Science. She co-directs the CSAIL Center for robotics and is an Associate Director of CSAIL. Her research interests center on distributed robotics and mobile computing, and she has published extensively in the field. Her work in robotics aims to develop self-organizing systems and spans the spectrum from novel mechanical design and experimental platforms to developing and analyzing algorithms for locomotion, manipulation, and group control. She has received a number of awards, including the MacArthur Fellow. She has been on the program committees of several international conferences, and has served the IEEE Robotics and Automation Society as Education Co-Chair.

## List of Contributors

### Jorge Angeles

McGill University  
Department of Mechanical Engineering  
and Centre for Intelligent Machines  
817 Sherbrooke St. W.  
Montreal, Quebec H3A 2K6, Canada  
e-mail: [angeles@cim.mcgill.ca](mailto:angeles@cim.mcgill.ca)

### Gianluca Antonelli

Università degli Studi di Cassino  
Dipartimento di Automazione, Ingegneria  
dell'Informazione e Matematica Industriale  
Via G. Di Biasio 43  
03043 Cassino, Italy  
e-mail: [antonelli@unicas.it](mailto:antonelli@unicas.it)

### Fumihito Arai

Tohoku University  
Department of Bioengineering and Robotics  
6-6-01 Aoba-yama  
980-8579 Sendai, Japan  
e-mail: [arai@imech.mech.tohoku.ac.jp](mailto:arai@imech.mech.tohoku.ac.jp)

### Michael A. Arbib

University of Southern California  
Computer, Neuroscience and USC Brain Project  
Los Angeles, CA 90089-2520, USA  
e-mail: [arbib@usc.edu](mailto:arbib@usc.edu)

### Antonio Bicchi

Università degli Studi di Pisa  
Centro Interdipartimentale di Ricerca  
"Enrico Piaggio" e Dipartimento  
di Sistemi Elettrici e Automazione  
Via Diotisalvi 2  
56125 Pisa, Italy  
e-mail: [bicchi@ing.unipi.it](mailto:bicchi@ing.unipi.it)

### Aude Billard

Ecole Polytechnique Federale de Lausanne (EPFL)  
Learning Algorithms and Systems Laboratory (LASA)  
STI-I2S-LASA  
1015 Lausanne, Switzerland  
e-mail: [aude.billard@epfl.ch](mailto:aude.billard@epfl.ch)

### John Billingsley

University of Southern Queensland  
Faculty of Engineering and Surveying  
Toowoomba QLD 4350, Australia  
e-mail: [billings@usq.edu.au](mailto:billings@usq.edu.au)

### Wayne Book

Georgia Institute of Technology  
G.W. Woodruff School of Mechanical Engineering  
771 Ferst Drive  
Atlanta, GA 30332-0405, USA  
e-mail: [wayne.book@me.gatech.edu](mailto:wayne.book@me.gatech.edu)

### Cynthia Breazeal

Massachusetts Institute of Technology  
The Media Lab  
20 Ames St.  
Cambridge, MA 02139, USA  
e-mail: [cynthiab@media.mit.edu](mailto:cynthiab@media.mit.edu)

### Oliver Brock

University of Massachusetts  
Robotics and Biology Laboratory  
140 Governors Drive  
Amherst, MA 01003, USA  
e-mail: [oli@cs.umass.edu](mailto:oli@cs.umass.edu)

### Alberto Broggi

Università degli Studi di Parma  
Dipartimento di Ingegneria dell'Informazione  
Viale delle Scienze 181A  
43100 Parma, Italy  
e-mail: [broggi@ce.unipr.it](mailto:broggi@ce.unipr.it)

### Heinrich H. Bühlhoff

Max-Planck-Institut für biologische Kybernetik  
Kognitive Humanpsychophysik  
Spemannstr. 38  
72076 Tübingen, Germany  
e-mail: [heinrich.buelthoff@tuebingen.mpg.de](mailto:heinrich.buelthoff@tuebingen.mpg.de)

**Joel W. Burdick**

California Institute of Technology  
Mechanical Engineering Department  
1200 E. California Blvd.  
Pasadena, CA 91125, USA  
e-mail: [jwb@robotics.caltech.edu](mailto:jwb@robotics.caltech.edu)

**Wolfram Burgard**

Albert-Ludwigs-Universität Freiburg  
Institut für Informatik  
Georges-Koehler-Allee 079  
79110 Freiburg, Germany  
e-mail: [burgard@informatik.uni-freiburg.de](mailto:burgard@informatik.uni-freiburg.de)

**Zack Butler**

Rochester Institute of Technology  
Department of Computer Science  
102 Lomb Memorial Dr.  
Rochester, NY 14623, USA  
e-mail: [zjb@cs.rit.edu](mailto:zjb@cs.rit.edu)

**Fabrizio Caccavale**

Università degli Studi della Basilicata  
Dipartimento di Ingegneria e Fisica dell'Ambiente  
Via dell'Ateneo Lucano 10  
85100 Potenza, Italy  
e-mail: [fabrizio.caccavale@unibas.it](mailto:fabrizio.caccavale@unibas.it)

**Sylvain Calinon**

Ecole Polytechnique Federale de Lausanne (EPFL)  
Learning Algorithms and Systems Laboratory (LASA)  
STI-I2S-LASA  
1015 Lausanne, Switzerland  
e-mail: [sylvain.calinon@epfl.ch](mailto:sylvain.calinon@epfl.ch)

**Guy Campion**

Université Catholique de Louvain  
Centre d'Ingénierie des Systèmes d'Automatique  
et de Mécanique Appliquée  
4 Avenue G. Lemaître  
1348 Louvain-la-Neuve, Belgium  
e-mail: [guy.campion@uclouvain.be](mailto:guy.campion@uclouvain.be)

**Raja Chatila**

LAAS-CNRS  
7 Avenue du Colonel Roche  
31077 Toulouse, France  
e-mail: [raja.chatila@laas.fr](mailto:raja.chatila@laas.fr)

**François Chaumette**

INRIA/IRISA  
Campus de Beaulieu  
35042 Rennes, France  
e-mail: [francois.chaumette@irisa.fr](mailto:francois.chaumette@irisa.fr)

**Stefano Chiaverini**

Università degli Studi di Cassino  
Dipartimento di Automazione, Ingegneria  
dell'Informazione e Matematica Industriale  
Via G. Di Biasio 43  
03043 Cassino, Italy  
e-mail: [chiaverini@unicas.it](mailto:chiaverini@unicas.it)

**Nak Young Chong**

Japan Advanced Institute of Science  
and Technology (JAIST)  
School of Information Science  
1-1 Asahidai, Nomi  
923-1292 Ishikawa, Japan  
e-mail: [nakyoung@jaist.ac.jp](mailto:nakyoung@jaist.ac.jp)

**Howie Choset**

Carnegie Mellon University  
The Robotics Institute  
5000 Forbes Ave.  
Pittsburgh, PA 15213, USA  
e-mail: [choset@cs.cmu.edu](mailto:choset@cs.cmu.edu)

**Henrik I. Christensen**

Georgia Institute of Technology  
Robotics and Intelligent Machines @ GT  
Atlanta, GA 30332-0760, USA  
e-mail: [hic@cc.gatech.edu](mailto:hic@cc.gatech.edu)

**Wankyun Chung**

POSTECH  
Department of Mechanical Engineering  
San 31 Hyojading  
Pohang 790-784, Korea  
e-mail: [wkchung@postech.ac.kr](mailto:wkchung@postech.ac.kr)

**Woojin Chung**

Korea University  
Department of Mechanical Engineering  
Anam-dong, Sungbuk-ku  
Seoul 136-701, Korea  
e-mail: [smartrobot@korea.ac.kr](mailto:smartrobot@korea.ac.kr)

**J. Edward Colgate**

Northwestern University  
 Department of Mechanical Engineering  
 Segal Design Institute  
 2145 Sheridan Rd.  
 Evanston, IL 60208, USA  
 e-mail: [colgate@northwestern.edu](mailto:colgate@northwestern.edu)

**Peter Corke**

Commonwealth Scientific  
 and Industrial Research Organisation (CSIRO)  
 ICT Centre  
 PO Box 883  
 Kenmore QLD 4069, Australia  
 e-mail: [peter.corke@csiro.au](mailto:peter.corke@csiro.au)

**Jock Cunningham**

Commonwealth Scientific  
 and Industrial Research Organisation (CSIRO)  
 Division of Exploration and Mining  
 PO Box 883  
 Kenmore QLD 4069, Australia  
 e-mail: [jock.cunningham@csiro.au](mailto:jock.cunningham@csiro.au)

**Mark R. Cutkosky**

Stanford University  
 Mechanical Engineering  
 Building 560, 424 Panama Mall  
 Stanford, CA 94305-2232, USA  
 e-mail: [cutkosky@stanford.edu](mailto:cutkosky@stanford.edu)

**Kostas Daniilidis**

University of Pennsylvania  
 Department of Computer and Information Science  
 GRASP Laboratory  
 3330 Walnut Street  
 Philadelphia, PA 19104, USA  
 e-mail: [kostas@cis.upenn.edu](mailto:kostas@cis.upenn.edu)

**Paolo Dario**

Scuola Superiore Sant'Anna  
 ARTS Lab e CRIM Lab  
 Piazza Martiri della Libertà 33  
 56127 Pisa, Italy  
 e-mail: [paolo.dario@sssup.it](mailto:paolo.dario@sssup.it)

**Alessandro De Luca**

Università degli Studi di Roma "La Sapienza"  
 Dipartimento di Informatica  
 e Sistemistica "A. Ruberti"  
 Via Ariosto 25  
 00185 Roma, Italy  
 e-mail: [deluca@dis.uniroma1.it](mailto:deluca@dis.uniroma1.it)

**Joris De Schutter**

Katholieke Universiteit Leuven  
 Department of Mechanical Engineering  
 Celestijnenlaan 300, Box 02420  
 3001 Leuven-Heverlee, Belgium  
 e-mail: [joris.deschutter@mech.kuleuven.be](mailto:joris.deschutter@mech.kuleuven.be)

**Rüdiger Dillmann**

Universität Karlsruhe  
 Institut für Technische Informatik  
 Haid-und-Neu-Str. 7  
 76131 Karlsruhe, Germany  
 e-mail: [dillmann@ira.uka.de](mailto:dillmann@ira.uka.de)

**Lixin Dong**

ETH Zentrum  
 Institute of Robotics and Intelligent Systems  
 Tannenstr. 3  
 8092 Zürich, Switzerland  
 e-mail: [ldong@ethz.ch](mailto:ldong@ethz.ch)

**Gregory Dudek**

McGill University  
 Department of Computer Science  
 3480 University Street  
 Montreal, QC H3Y 3H4, Canada  
 e-mail: [dudek@cim.mcgill.ca](mailto:dudek@cim.mcgill.ca)

**Mark Dunn**

University of Southern Queensland  
 National Centre for Engineering in Agriculture  
 Toowoomba QLD 4350, Australia  
 e-mail: [mark.dunn@usq.edu.au](mailto:mark.dunn@usq.edu.au)

**Hugh Durrant-Whyte**

University of Sydney  
 ARC Centre of Excellence for Autonomous Systems  
 Australian Centre for Field Robotics (ACFR)  
 Sydney NSW 2006, Australia  
 e-mail: [hugh@acfr.usyd.edu.au](mailto:hugh@acfr.usyd.edu.au)



**Jan-Olof Eklundh**

KTH Royal Institute of Technology  
Teknikringen 14  
10044 Stockholm, Sweden  
e-mail: [joe@nada.kth.se](mailto:joe@nada.kth.se)

**Aydan M. Erkmen**

Middle East Technical University  
Department of Electrical Engineering  
Ankara, 06531, Turkey  
e-mail: [aydan@metu.edu.tr](mailto:aydan@metu.edu.tr)

**Bernard Espiau**

INRIA Rhône-Alpes  
38334 Saint-Ismier, France  
e-mail: [bernard.espiau@inria.fr](mailto:bernard.espiau@inria.fr)

**Roy Featherstone**

The Australian National University  
Department of Information Engineering  
RSISE Building 115  
Canberra ACT 0200, Australia  
e-mail: [roy.featherstone@anu.edu.au](mailto:roy.featherstone@anu.edu.au)

**Eric Feron**

Georgia Institute of Technology  
School of Aerospace Engineering  
270 Ferst Drive  
Atlanta, GA 30332-0150, USA  
e-mail: [feron@gatech.edu](mailto:feron@gatech.edu)

**Gabor Fichtinger**

Queen's University  
School of Computing  
#725 Goodwin Hall, 25 Union St.  
Kingston, ON K7L 3N6, Canada  
e-mail: [gabor@cs.queensu.ca](mailto:gabor@cs.queensu.ca)

**Paolo Fiorini**

Università degli Studi di Verona  
Dipartimento di Informatica  
Strada le Grazie 15  
37134 Verona, Italy  
e-mail: [paolo.fiorini@univr.it](mailto:paolo.fiorini@univr.it)

**Robert B. Fisher**

University of Edinburgh  
School of Informatics  
James Clerk Maxwell Building, Mayfield Road  
Edinburgh, EH9 3JZ, UK  
e-mail: [rbr@inf.ed.ac.uk](mailto:rbr@inf.ed.ac.uk)

**Paul Fitzpatrick**

Italian Institute of Technology  
Robotics, Brain, and Cognitive  
Sciences Department  
Via Morego 30  
16163 Genova, Italy  
e-mail: [paul.fitzpatrick@iit.it](mailto:paul.fitzpatrick@iit.it)

**Dario Floreano**

Ecole Polytechnique Federale de Lausanne (EPFL)  
Laboratory of Intelligent Systems  
EPFL-STI-I2S-LIS  
1015 Lausanne, Switzerland  
e-mail: [dario.floreano@epfl.ch](mailto:dario.floreano@epfl.ch)

**Thor I. Fossen**

Norwegian University of Science  
and Technology (NTNU)  
Department of Engineering Cybernetics  
Trondheim, 7491, Norway  
e-mail: [fossen@ieee.org](mailto:fossen@ieee.org)

**Li-Chen Fu**

National Taiwan University  
Department of Electrical Engineering  
Taipei, 106, Taiwan, R.O.C.  
e-mail: [lichen@ntu.edu.tw](mailto:lichen@ntu.edu.tw)

**Maxime Gautier**

Université de Nantes  
IRCCyN, ECN  
1 Rue de la Noë  
44321 Nantes, France  
e-mail: [maxime.gautier@ircryn.ec-nantes.fr](mailto:maxime.gautier@ircryn.ec-nantes.fr)

**Martin A. Giese**

University of Wales  
Department of Psychology  
Penrallt Rd.  
Bangor, LL 57 2AS, UK  
e-mail: [martin.giese@uni-tuebingen.de](mailto:martin.giese@uni-tuebingen.de)

**Ken Goldberg**

University of California at Berkeley  
 Department of Industrial Engineering  
 and Operations Research  
 4141 Etcheverry Hall  
 Berkeley, CA 94720-1777, USA  
 e-mail: [goldberg@jeor.berkeley.edu](mailto:goldberg@jeor.berkeley.edu)

**Clément Gosselin**

Université Laval  
 Département de Genie Mecanique  
 Quebec, QC G1K 7P4, Canada  
 e-mail: [gosselin@gmc.ulaval.ca](mailto:gosselin@gmc.ulaval.ca)

**Agnès Guillot**

Université Pierre et Marie Curie – CNRS  
 Institut des Systèmes Intelligents et de Robotique  
 4 Place Jussieu  
 75252 Paris, France  
 e-mail: [agnes.guillot@lip6.fr](mailto:agnes.guillot@lip6.fr)

**Martin Hägele**

Fraunhofer IPA  
 Robot Systems  
 Nobelstr. 12  
 70569 Stuttgart, Germany  
 e-mail: [mmh@ipa.fhg.de](mailto:mmh@ipa.fhg.de)

**Gregory D. Hager**

Johns Hopkins University  
 Department of Computer Science  
 3400 N. Charles St.  
 Baltimore, MD 21218, USA  
 e-mail: [hager@cs.jhu.edu](mailto:hager@cs.jhu.edu)

**David Hainsworth**

Commonwealth Scientific  
 and Industrial Research Organisation (CSIRO)  
 Division of Exploration and Mining  
 PO Box 883  
 Kenmore QLD 4069, Australia  
 e-mail: [david.hainsworth@csiro.au](mailto:david.hainsworth@csiro.au)

**William R. Hamel**

University of Tennessee  
 Mechanical, Aerospace,  
 and Biomedical Engineering  
 414 Dougherty Engineering Building  
 Knoxville, TN 37996-2210, USA  
 e-mail: [whamel@utk.edu](mailto:whamel@utk.edu)

**Blake Hannaford**

University of Washington  
 Department of Electrical Engineering  
 Box 352500  
 Seattle, WA 98195-2500, USA  
 e-mail: [blake@ee.washington.edu](mailto:blake@ee.washington.edu)

**Kensuke Harada**

National Institute of Advanced Industrial Science  
 and Technology (AIST)  
 Intelligent Systems Research Institute  
 1-1-1 Umezono  
 305-8568 Tsukuba, Japan  
 e-mail: [kensuke.harada@aist.go.jp](mailto:kensuke.harada@aist.go.jp)

**Martial Hebert**

Carnegie Mellon University  
 The Robotics Institute  
 5000 Forbes Ave.  
 Pittsburgh, PA 15213, USA  
 e-mail: [hebert@ri.cmu.edu](mailto:hebert@ri.cmu.edu)

**Thomas C. Henderson**

University of Utah  
 School of Computing  
 50 S. Central Campus Dr. 3190 MEB  
 Salt Lake City, UT 84112, USA  
 e-mail: [tch@cs.utah.edu](mailto:tch@cs.utah.edu)

**Joachim Hertzberg**

Universität Osnabrück  
 Institut für Informatik  
 Albrechtstr. 28  
 54076 Osnabrück, Germany  
 e-mail: [hertzberg@informatik.uni-osnabrueck.de](mailto:hertzberg@informatik.uni-osnabrueck.de)

**Hirohisa Hirukawa**

National Institute of Advanced Industrial Science  
and Technology (AIST)  
Intelligent Systems Research Institute  
1-1-1 Umezono  
305-8568 Tsukuba, Japan  
e-mail: [hiro.hirukawa@aist.go.jp](mailto:hiro.hirukawa@aist.go.jp)

**Gerd Hirzinger**

Deutsches Zentrum für Luft- und Raumfahrt (DLR)  
Oberpfaffenhofen  
Institut für Robotik und Mechatronik  
Münchner Str. 20  
82230 Wessling, Germany  
e-mail: [gerd.hirzinger@dlr.de](mailto:gerd.hirzinger@dlr.de)

**John Hollerbach**

University of Utah  
School of Computing  
50 S. Central Campus Dr.  
Salt Lake City, UT 84112, USA  
e-mail: [jmh@cs.utah.edu](mailto:jmh@cs.utah.edu)

**Robert D. Howe**

Harvard University  
Division of Engineering and Applied Sciences  
Pierce Hall, 29 Oxford St.  
Cambridge, MA 02138, USA  
e-mail: [howe@seas.harvard.edu](mailto:howe@seas.harvard.edu)

**Su-Hau Hsu<sup>†</sup>**

National Taiwan University  
Taipei, Taiwan

**Phil Husbands**

University of Sussex  
Department of Informatics  
Falmer, Brighton BN1 9QH, UK  
e-mail: [philh@sussex.ac.uk](mailto:philh@sussex.ac.uk)

**Seth Hutchinson**

University of Illinois  
Department of Electrical and Computer  
Engineering  
Urbana, IL 61801, USA  
e-mail: [seth@uiuc.edu](mailto:seth@uiuc.edu)

**Adam Jacoff**

National Institute of Standards and Technology  
Intelligent Systems Division  
100 Bureau Drive  
Gaithersburg, MD 20899, USA  
e-mail: [adam.jacoff@nist.gov](mailto:adam.jacoff@nist.gov)

**Michael Jenkin**

York University  
Computer Science and Engineering  
4700 Keel St.  
Toronto, Ontario M3J 1P3, Canada  
e-mail: [jenkin@cse.yorku.ca](mailto:jenkin@cse.yorku.ca)

**Eric N. Johnson**

Georgia Institute of Technology  
Daniel Guggenheim School of  
Aerospace Engineering  
270 Ferst Drive  
Atlanta, GA 30332-0150, USA  
e-mail: [eric.johnson@ae.gatech.edu](mailto:eric.johnson@ae.gatech.edu)

**Shuuji Kajita**

National Institute of Advanced Industrial Science  
and Technology (AIST)  
Intelligent Systems Research Institute  
1-1-1 Umezono  
305-8568 Tsukuba, Japan  
e-mail: [s.kajita@aist.go.jp](mailto:s.kajita@aist.go.jp)

**Makoto Kaneko**

Osaka University  
Department of Mechanical Engineering  
Graduate School of Engineering  
2-1 Yamadaoka  
565-0871 Suita, Osaka, Japan  
e-mail: [mk@mech.eng.osaka-u.ac.jp](mailto:mk@mech.eng.osaka-u.ac.jp)

**Sung-Chul Kang**

Korea Institute of Science and Technology  
Cognitive Robotics Research Center  
Hawolgok-dong 39-1, Sungbuk-ku  
Seoul 136-791, Korea  
e-mail: [kasch@kist.re.kr](mailto:kasch@kist.re.kr)

**Imin Kao**

State University of New York at Stony Brook  
 Department of Mechanical Engineering  
 Stony Brook, NY 11794-2300, USA  
 e-mail: [imin.kao@stonybrook.edu](mailto:imin.kao@stonybrook.edu)

**Lydia E. Kavradi**

Rice University  
 Department of Computer Science, MS 132  
 6100 Main Street  
 Houston, TX 77005, USA  
 e-mail: [kavraki@rice.edu](mailto:kavraki@rice.edu)

**Homayoon Kazerooni**

University of California at Berkeley  
 Berkeley Robotics and Human Engineering  
 Laboratory  
 5124 Etcheverry Hall  
 Berkeley, CA 94720-1740, USA  
 e-mail: [kazerooni@berkeley.edu](mailto:kazerooni@berkeley.edu)

**Charles C. Kemp**

Georgia Institute of Technology  
 and Emory University  
 The Wallace H. Coulter Department  
 of Biomedical Engineering  
 313 Ferst Drive  
 Atlanta, GA 30332-0535, USA  
 e-mail: [charlie.kemp@bme.gatech.edu](mailto:charlie.kemp@bme.gatech.edu)

**Wisama Khalil**

Université de Nantes  
 IRCCyN, ECN  
 1 Rue de la Noë  
 44321 Nantes, France  
 e-mail: [wisama.khalil@ircryn.ec-nantes.fr](mailto:wisama.khalil@ircryn.ec-nantes.fr)

**Oussama Khatib**

Stanford University  
 Department of Computer Science  
 Artificial Intelligence Laboratory  
 Stanford, CA 94305-9010, USA  
 e-mail: [khatib@cs.stanford.edu](mailto:khatib@cs.stanford.edu)

**Lindsay Kleeman**

Monash University  
 Department of Electrical and Computer Systems  
 Engineering  
 Department of ECSEng  
 Monash VIC 3800, Australia  
 e-mail: [kleeman@eng.monash.edu.au](mailto:kleeman@eng.monash.edu.au)

**Tetsunori Kobayashi**

Waseda University  
 Department of Computer Science  
 3-4-1 Okubo, Shinjuku-ku  
 169-8555 Tokyo, Japan  
 e-mail: [koba@waseda.jp](mailto:koba@waseda.jp)

**Kurt Konolige**

SRI International  
 Artificial Intelligence Center  
 333 Ravenswood Ave.  
 Menlo Park, CA 94025, USA  
 e-mail: [konolige@ai.sri.com](mailto:konolige@ai.sri.com)

**David Kortenkamp**

TRAC Labs Inc.  
 1012 Hercules Drive  
 Houston, TX 77058, USA  
 e-mail: [korten@traclabs.com](mailto:korten@traclabs.com)

**Kazuhiro Kosuge**

Tohoku University  
 Department of Bioengineering and Robotics  
 Graduate School of Engineering  
 6-6-01 Aoba-yama  
 980-8579 Sendai, Japan  
 e-mail: [kosuge@irs.mech.tohoku.ac.jp](mailto:kosuge@irs.mech.tohoku.ac.jp)

**Roman Kuc**

Yale University  
 Department of Electrical Engineering  
 10 Hillhouse Ave  
 New Haven, CT 06520-8267, USA  
 e-mail: [kuc@yale.edu](mailto:kuc@yale.edu)

**James Kuffner**

Carnegie Mellon University  
 The Robotics Institute  
 5000 Forbes Ave.  
 Pittsburgh, PA 15213, USA  
 e-mail: [kuffner@cs.cmu.edu](mailto:kuffner@cs.cmu.edu)

**Vijay Kumar**

University of Pennsylvania  
Department of Mechanical Engineering  
and Applied Mechanics  
220 S. 33rd Street  
Philadelphia, PA 19104-6315, USA  
e-mail: [kumar@grasp.upenn.edu](mailto:kumar@grasp.upenn.edu)

**Florent Lamiroux**

LAAS-CNRS  
7 Avenue du Colonel Roche  
31077 Toulouse, France  
e-mail: [florent@laas.fr](mailto:florent@laas.fr)

**Jean-Paul Laumond**

LAAS-CNRS  
7 Avenue du Colonel Roche  
31077 Toulouse, France  
e-mail: [jpl@laas.fr](mailto:jpl@laas.fr)

**Steven M. LaValle**

University of Illinois  
Department of Computer Science  
201 N. Goodwin Ave, 3318 Siebel Center  
Urbana, IL 61801, USA  
e-mail: [lavalle@cs.uiuc.edu](mailto:lavalle@cs.uiuc.edu)

**John J. Leonard**

Massachusetts Institute of Technology  
Department of Mechanical Engineering  
5-214 77 Massachusetts Ave  
Cambridge, MA 02139, USA  
e-mail: [jleonard@mit.edu](mailto:jleonard@mit.edu)

**Kevin Lynch**

Northwestern University  
Mechanical Engineering Department  
2145 Sheridan Road  
Evanston, IL 60208, USA  
e-mail: [kmlynch@northwestern.edu](mailto:kmlynch@northwestern.edu)

**Alan M. Lytle**

National Institute of Standards and Technology  
Construction Metrology and Automation Group  
100 Bureau Drive  
Gaithersburg, MD 20899, USA  
e-mail: [alan.lytle@nist.gov](mailto:alan.lytle@nist.gov)

**Maja J. Mataric**

University of Southern California  
Computer Science Department  
3650 McClintock Avenue  
Los Angeles, CA 90089, USA  
e-mail: [mataric@usc.edu](mailto:mataric@usc.edu)

**Yoshio Matsumoto**

Osaka University  
Department of Adaptive Machine Systems  
Graduate School of Engineering  
565-0871 Suita, Osaka, Japan  
e-mail: [matsumoto@ams.eng.osaka-u.ac.jp](mailto:matsumoto@ams.eng.osaka-u.ac.jp)

**J. Michael McCarthy**

University of California at Irvine  
Department of Mechanical and Aerospace  
Engineering  
Irvine, CA 92697, USA  
e-mail: [jmmccart@uci.edu](mailto:jmmccart@uci.edu)

**Claudio Melchiorri**

Università degli Studi di Bologna  
Dipartimento di Elettronica Informatica  
e Sistemistica  
Via Risorgimento 2  
40136 Bologna, Italy  
e-mail: [claudio.melchiorri@unibo.it](mailto:claudio.melchiorri@unibo.it)

**Arianna Menciassi**

Scuola Superiore Sant'Anna  
CRIM Lab  
Piazza Martiri della Libertà 33  
56127 Pisa, Italy  
e-mail: [arianna@sssup.it](mailto:arianna@sssup.it)

**Jean-Pierre Merlet**

INRIA Sophia-Antipolis  
2004 Route des Lucioles  
06902 Sophia-Antipolis, France  
e-mail: [jean-pierre.merlet@sophia.inria.fr](mailto:jean-pierre.merlet@sophia.inria.fr)

**Giorgio Metta**

Italian Institute of Technology  
Department of Robotics, Brain and Cognitive  
Sciences  
Via Morego 30  
16163 Genova, Italy  
e-mail: [pasa@liralab.it](mailto:pasa@liralab.it)

**Jean-Arcady Meyer**

Université Pierre et Marie Curie – CNRS  
 Institut des Systèmes Intelligents et de Robotique  
 4 Place Jussieu  
 75252 Paris, France  
 e-mail: [jean-arcady.meyer@lip6.fr](mailto:jean-arcady.meyer@lip6.fr)

**François Michaud**

Université de Sherbrooke  
 Department of Electrical Engineering  
 and Computer Engineering  
 2500 Boulevard Université  
 Sherbrooke, Québec J1K 2R1, Canada  
 e-mail: [francois.michaud@usherbrooke.ca](mailto:francois.michaud@usherbrooke.ca)

**David P. Miller**

University of Oklahoma  
 School of Aerospace and Mechanical Engineering  
 865 Asp Ave.  
 Norman, OK 73019, USA  
 e-mail: [dpmiller@ou.edu](mailto:dpmiller@ou.edu)

**Javier Minguez**

Universidad de Zaragoza  
 Departamento de Informática e Ingeniería de  
 Sistemas  
 Centro Politécnico Superior  
 Edificio Ada Byron, Maria de Luna 1  
 Zaragoza 50018, Spain  
 e-mail: [jminguez@unizar.es](mailto:jminguez@unizar.es)

**Pascal Morin**

INRIA Sophia-Antipolis  
 2004 Route des Lucioles  
 06902 Sophia-Antipolis, France  
 e-mail: [pascal.morin@inria.fr](mailto:pascal.morin@inria.fr)

**Robin R. Murphy**

University of South Florida  
 Computer Science and Engineering  
 4202 E. Fowler Ave ENB342  
 Tampa, FL 33620-5399, USA  
 e-mail: [murphy@cse.usf.edu](mailto:murphy@cse.usf.edu)

**Daniele Nardi**

Università degli Studi di Roma "La Sapienza"  
 Dipartimento di Informatica e Sistemistica  
 "A. Ruberti"  
 Via Ariosto 25  
 00185 Roma, Italy  
 e-mail: [nardi@dis.uniroma1.it](mailto:nardi@dis.uniroma1.it)

**Bradley J. Nelson**

ETH Zentrum  
 Institute of Robotics and Intelligent Systems  
 Tannenstr. 3  
 8092 Zürich, Switzerland  
 e-mail: [bnelson@ethz.ch](mailto:bnelson@ethz.ch)

**Günter Niemeyer**

Stanford University  
 Department of Mechanical Engineering  
 Design Group, Terman Engineering Center  
 Stanford, CA 94305-4021, USA  
 e-mail: [gunter.niemeyer@stanford.edu](mailto:gunter.niemeyer@stanford.edu)

**Klas Nilsson**

Lund University  
 Department of Computer Science  
 Ole Römers väg 3  
 22100 Lund, Sweden  
 e-mail: [klas@cs.lu.se](mailto:klas@cs.lu.se)

**Stefano Nolfi**

Consiglio Nazionale delle Ricerche (CNR)  
 Istituto di Scienze e Tecnologie della Cognizione  
 Via S. Martino della Battaglia 44  
 00185 Roma, Italy  
 e-mail: [stefano.nolfi@istc.cnr.it](mailto:stefano.nolfi@istc.cnr.it)

**Illah R. Nourbakhsh**

Carnegie Mellon University  
 The Robotics Institute  
 5000 Forbes Ave.  
 Pittsburgh, PA 15213, USA  
 e-mail: [illah@cs.cmu.edu](mailto:illah@cs.cmu.edu)

**Jonathan B. O'Brien**

University of New South Wales  
 School of Civil and Environmental Engineering  
 Sydney 2052, Australia  
 e-mail: [j.obrien@unsw.edu.au](mailto:j.obrien@unsw.edu.au)

**Allison M. Okamura**

The Johns Hopkins University  
Department of Mechanical Engineering  
3400 N. Charles Street  
Baltimore, MD 21218, USA  
e-mail: [aokamura@jhu.edu](mailto:aokamura@jhu.edu)

**Fiorella Operto**

Scuola di Robotica  
Piazza Monastero 4  
16149 Sampierdarena, Genova, Italy  
e-mail: [operto@scuoladirobotica.it](mailto:operto@scuoladirobotica.it)

**David E. Orin**

The Ohio State University  
Department of Electrical Engineering  
2015 Neil Avenue  
Columbus, OH 43210, USA  
e-mail: [orin.1@osu.edu](mailto:orin.1@osu.edu)

**Giuseppe Oriolo**

Università degli Studi di Roma "La Sapienza"  
Dipartimento di Informatica e Sistemistica  
"A. Ruberti"  
Via Ariosto 25  
00185 Roma, Italy  
e-mail: [oriolo@dis.uniroma1.it](mailto:oriolo@dis.uniroma1.it)

**Michel Parent**

INRIA Rocquencourt  
78153 Le Chesnay, France  
e-mail: [michel.parent@inria.fr](mailto:michel.parent@inria.fr)

**Frank C. Park**

Seoul National University  
Mechanical and Aerospace Engineering  
Seoul 51-742, Korea  
e-mail: [fcpark@snu.ac.kr](mailto:fcpark@snu.ac.kr)

**Lynne E. Parker**

University of Tennessee  
Department of Electrical Engineering  
and Computer Science  
1122 Volunteer Blvd.  
Knoxville, TN 37996-3450, USA  
e-mail: [parker@eecs.utk.edu](mailto:parker@eecs.utk.edu)

**Michael A. Peshkin**

Northwestern University  
Department of Mechanical Engineering  
2145 Sheridan Road  
Evanston, IL 60208, USA  
e-mail: [peshkin@northwestern.edu](mailto:peshkin@northwestern.edu)

**J. Norberto Pires**

Universidade de Coimbra  
Departamento de Engenharia Mecânica  
Polo II  
Coimbra 3030, Portugal  
e-mail: [norberto@robotics.dem.uc.pt](mailto:norberto@robotics.dem.uc.pt)

**Erwin Prassler**

Fachhochschule Bonn-Rhein-Sieg  
Fachbereich Informatik  
Grantham-Allee 20  
53757 Sankt Augustin, Germany  
e-mail: [erwin.prassler@fh-brs.de](mailto:erwin.prassler@fh-brs.de)

**Domenico Prattichizzo**

Università degli Studi di Siena  
Dipartimento di Ingegneria dell'Informazione  
Via Roma 56  
53100 Siena, Italy  
e-mail: [prattichizzo@ing.unisi.it](mailto:prattichizzo@ing.unisi.it)

**Carsten Preusche**

Deutsches Zentrum für Luft- und Raumfahrt (DLR)  
Oberpfaffenhofen  
Institut für Robotik und Mechatronik  
Münchner Str. 20  
82234 Wessling, Germany  
e-mail: [carsten.preusche@dlr.de](mailto:carsten.preusche@dlr.de)

**William R. Provancher**

University of Utah  
Department of Mechanical Engineering  
50 S. Central Campus, 2120 MEB  
Salt Lake City, UT 84112-9208, USA  
e-mail: [wil@mech.utah.edu](mailto:wil@mech.utah.edu)

**David J. Reinkensmeyer**

University of California at Irvine  
Mechanical and Aerospace Engineering  
4200 Engineering Gateway  
Irvine, CA 92617-3975, USA  
e-mail: [dreinken@uci.edu](mailto:dreinken@uci.edu)

**Alfred Rizzi**

Boston Dynamics  
78 Fourth Ave  
Waltham, MA 02451, USA  
e-mail: [arizzi@bostondynamics.com](mailto:arizzi@bostondynamics.com)

**Jonathan Roberts**

Commonwealth Scientific  
and Industrial Research Organisation (CSIRO)  
ICT Centre, Autonomous Systems Laboratory  
P.O. Box 883  
Kenmore QLD 4069, Australia  
e-mail: [jonathan.roberts@csiro.au](mailto:jonathan.roberts@csiro.au)

**Daniela Rus**

Massachusetts Institute of Technology  
CSAIL Center for Robotics  
32 Vassar Street  
Cambridge, MA 01239, USA  
e-mail: [rus@csail.mit.edu](mailto:rus@csail.mit.edu)

**Kamel S. Saidi**

National Institute of Standards and Technology  
Building and Fire Research Laboratory  
100 Bureau Drive  
Gaithersburg, MD 20899, USA  
e-mail: [kamel.saidi@nist.gov](mailto:kamel.saidi@nist.gov)

**Claude Samson**

INRIA Sophia-Antipolis  
2004 Route des Lucioles  
06902 Sophia-Antipolis, France  
e-mail: [claudio.samson@inria.fr](mailto:claudio.samson@inria.fr)

**Stefan Schaal**

University of Southern California  
Computer Science and Neuroscience  
3710 S. McClintock Ave.  
Los Angeles, CA 90089-2905, USA  
e-mail: [sschaal@usc.edu](mailto:sschaal@usc.edu)

**Victor Scheinman**

Stanford University  
Department of Mechanical Engineering  
Stanford, CA 94305, USA  
e-mail: [vds@stanford.edu](mailto:vds@stanford.edu)

**James Schmiedeler**

The Ohio State University  
Department of Mechanical Engineering  
E307 Scott Laboratory, 201 West 19th Ave  
Columbus, OH 43210, USA  
e-mail: [schmiedeler.2@osu.edu](mailto:schmiedeler.2@osu.edu)

**Bruno Siciliano**

Università degli Studi di Napoli Federico II  
Dipartimento di Informatica e Sistemistica,  
PRISMA Lab  
Via Claudio 21  
80125 Napoli, Italy  
e-mail: [siciliano@unina.it](mailto:siciliano@unina.it)

**Roland Siegwart**

ETH Zentrum  
Department of Mechanical and Process  
Engineering  
Tannenstr. 3, CLA E32  
8092 Zürich, Switzerland  
e-mail: [rsiegwart@ethz.ch](mailto:rsiegwart@ethz.ch)

**Reid Simmons**

Carnegie Mellon University  
The Robotics Institute  
School of Computer Science  
5000 Forbes Ave.  
Pittsburgh, PA 15241, USA  
e-mail: [reids@cs.cmu.edu](mailto:reids@cs.cmu.edu)

**Dezhen Song**

Texas A&M University  
Department of Computer Science  
H.R. Bright Building  
College Station, TX 77843, USA  
e-mail: [dzsong@cs.tamu.edu](mailto:dzsong@cs.tamu.edu)

**Gaurav S. Sukhatme**

University of Southern California  
Department of Computer Science  
3710 South McClintock Ave  
Los Angeles, CA 90089-2905, USA  
e-mail: [gaurav@usc.edu](mailto:gaurav@usc.edu)



**Satoshi Tadokoro**

Tohoku University  
Graduate School of Information Sciences  
6-6-01 Aoba-yama  
980-8579 Sendai, Japan  
e-mail: [tadokoro@rm.is.tohoku.ac.jp](mailto:tadokoro@rm.is.tohoku.ac.jp)

**Atsuo Takanishi**

Waseda University  
Department of Modern Mechanical Engineering  
3-4-1 Ookubo, Shinjuku-ku  
169-8555 Tokyo, Japan  
e-mail: [takanisi@waseda.jp](mailto:takanisi@waseda.jp)

**Russell H. Taylor**

The Johns Hopkins University  
Department of Computer Science  
Computational Science and Engineering Building  
1-127, 3400 North Charles Street  
Baltimore, MD 21218, USA  
e-mail: [rht@jhu.edu](mailto:rht@jhu.edu)

**Charles E. Thorpe**

Carnegie Mellon University in Qatar  
Qatar Office SMC 1070  
5032 Forbes Ave.  
Pittsburgh, PA 15289, USA  
e-mail: [thorpe@qatar.cmu.edu](mailto:thorpe@qatar.cmu.edu)

**Sebastian Thrun**

Stanford University  
Department of Computer Science  
Artificial Intelligence Laboratory  
Stanford, CA 94305-9010, USA  
e-mail: [thrun@stanford.edu](mailto:thrun@stanford.edu)

**James P. Trevelyan**

The University of Western Australia  
School of Mechanical Engineering  
35 Stirling Highway, Crawley  
Perth Western Australia 6009, Australia  
e-mail: [james.trevelyan@uwa.edu.au](mailto:james.trevelyan@uwa.edu.au)

**Jeffrey C. Trinkle**

Rensselaer Polytechnic Institute  
Department of Computer Science  
Troy, NY 12180-3590, USA  
e-mail: [trink@cs.rpi.edu](mailto:trink@cs.rpi.edu)

**Masaru Uchiyama**

Tohoku University  
Department of Aerospace Engineering  
6-6-01 Aoba-yama  
980-8579 Sendai, Japan  
e-mail: [uchiyama@space.mech.tohoku.ac.jp](mailto:uchiyama@space.mech.tohoku.ac.jp)

**H.F. Machiel Van der Loos**

University of British Columbia  
Department of Mechanical Engineering  
6250 Applied Science Lane  
Vancouver, BC V6T 1Z4, Canada  
e-mail: [vdl@mech.ubc.ca](mailto:vdl@mech.ubc.ca)

**Patrick van der Smagt**

Deutsches Zentrum für Luft- und Raumfahrt (DLR)  
Oberpfaffenhofen  
Institut für Robotik und Mechatronik  
Münchner Str. 20  
82230 Wessling, Germany  
e-mail: [smagt@dlr.de](mailto:smagt@dlr.de)

**Gianmarco Veruggio**

Consiglio Nazionale delle Ricerche  
Istituto di Elettronica e di Ingegneria  
dell'Informazione e delle Telecomunicazioni  
Via De Marini 6  
16149 Genova, Italy  
e-mail: [gianmarco@veruggio.it](mailto:gianmarco@veruggio.it)

**Luigi Villani**

Università degli Studi di Napoli Federico II  
Dipartimento di Informatica e Sistemistica,  
PRISMA Lab  
Via Claudio 21  
80125 Napoli, Italy  
e-mail: [luigi.villani@unina.it](mailto:luigi.villani@unina.it)

**Arto Visala**

Helsinki University of Technology (TKK)  
Department of Automation and Systems  
Technology  
Helsinki 02015, Finland  
e-mail: [arto.visala@tkk.fi](mailto:arto.visala@tkk.fi)

**Kenneth Waldron**

Stanford University  
Department of Mechanical Engineering  
Terman Engineering Center 521  
Stanford, CA 94305-4021, USA  
e-mail: [kwaldron@stanford.edu](mailto:kwaldron@stanford.edu)

**Ian D. Walker**

Clemson University  
Department of Electrical and Computer  
Engineering  
Clemson, SC 29634, USA  
e-mail: [ianw@ces.clemson.edu](mailto:ianw@ces.clemson.edu)

**Christian Wallraven**

Max-Planck-Institut für biologische Kybernetik  
Kognitive Humanpsychophysik  
Spemannstr. 38  
72076 Tübingen, Germany  
e-mail: [christian.wallraven@tuebingen.mpg.de](mailto:christian.wallraven@tuebingen.mpg.de)

**Brian Wilcox**

California Institute of Technology  
Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, CA 91109, USA  
e-mail: [brian.h.wilcox@jpl.nasa.gov](mailto:brian.h.wilcox@jpl.nasa.gov)

**Jing Xiao**

University of North Carolina  
Department of Computer Science  
Charlotte, NC 28223, USA  
e-mail: [xiao@uncc.edu](mailto:xiao@uncc.edu)

**Dana R. Yoerger**

Woods Hole Oceanographic Institution  
Department of Applied Ocean Physics  
and Engineering  
MS7 Blake Bldg.  
Woods Hole, MA 02543, USA  
e-mail: [dyoerger@whoi.edu](mailto:dyoerger@whoi.edu)

**Kazuhito Yokoi**

National Institute of Advanced Industrial Science  
and Technology (AIST)  
Intelligent Systems Research Institute  
1-1-1 Umezono  
305-8568 Tsukuba, Japan  
e-mail: [kazuhito.yokoi@aist.go.jp](mailto:kazuhito.yokoi@aist.go.jp)

**Kazuya Yoshida**

Tohoku University  
Department of Aerospace Engineering  
6-6-01 Aoba-yama  
980-8579 Sendai, Japan  
e-mail: [yoshida@astro.mech.tohoku.ac.jp](mailto:yoshida@astro.mech.tohoku.ac.jp)

**Alexander Zelinsky**

Commonwealth Scientific  
and Industrial Research Organisation (CSIRO)  
ICT Centre  
Epping, Sydney NSW 1710, Australia  
e-mail: [alex.zelinsky@csiro.au](mailto:alex.zelinsky@csiro.au)

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## List of Abbreviations

<b>A</b>		<b>B</b>	
AAAI	American Association for Artificial Intelligence	BIROB	biomimetic robotics
ABA	articulated-body algorithm	BLDC	brushless direct current
ABRT	automated bus rapid transit	BLE	broadcast of local eligibility
ACAS	airborne collision avoidance systems	BLEEX	Berkeley lower-extremity exoskeleton
ACC	adaptive cruise control	BLUE	best linear unbiased estimator
ACM	active cord mechanism	BN	Bayes network
ACM	Association of Computing Machinery	BRT	bus rapid transit
ADAS	advanced driver assistance systems	<b>C</b>	
ADL	activities of daily living	C/A	coarse-acquisition
ADSL	asymmetric digital subscriber line	CAM	computer-aided manufacturing
AGV	automated guided vehicles	CAD	computer-aided design
AHS	advanced highway systems	CAE	computer-aided engineering
AI	artificial intelligence	CALM	continuous air interface long and medium range
AIP	anterior interparietal area	CAN	controller area network
AIS	artificial intelligence (AI) system	CARD	computer-aided remote driving
AISB	artificial intelligence and simulation o behavior	CASPER	continuous activity scheduling, planning, execution and replanning
AIT	anterior inferotemporal cortex	CAT	computer-aided tomography
AM	actuators for manipulation	CB	cluster bombs
AMA	artificial moral agents	CCD	charge-coupled devices
AMD	autonomous mental development	CCI	control command interpreter
ANSI	American National Standards Institute	CCP	coverage configuration protocol
AP	antipersonnel	CCT	conservative congruence transformation
APG	adjustable pattern generator	CCW	counterclockwise
AR	augmented reality	CE	computer ethics
ARAMIS	Space Application of Automation, Robotics and Machine Intelligence	CEA	Commission de Energie Atomique
ASCL	adaptive seek control logic	CEBOT	cellular robot
ASD	autism spectrum disorder	CF	climbing fibers
ASIC	application-specific integrated circuit	CF	contact formation
ASKA	receptionist robot	CG	center of gravity
ASM	advanced servomanipulator	CGA	clinical gait analysis
ASN	active sensor network	CGI	common gateway interface
ASTRO	autonomous space transport robotic operations	CIE	International Commission on Illumination
ASV	adaptive suspension vehicle	CIRCA	cooperative intelligent real-time control architecture
AT	antitank	CIS	computer-integrated surgery
ATLSS	advanced technology for large structural systems	CLARAty	coupled layered architecture for robot autonomy
ATR	Advanced Telecommunications Research Institute International	CLEaR	closed-loop execution and recovery
AuRA	autonomous robot architecture	CLIK	closed-loop inverse kinematics
AUV	autonomous underwater vehicles	CMAC	cerebellar model articulation controller
AV	antivehicle	CML	concurrent mapping and localization
		CNC	computer numerical control
		CNP	contract net protocol

CNT carbon nanotubes  
 COG center of gravity  
 CONE Collaborative Observatory for Nature  
 Environments

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

---

**D**


---

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

DVL Doppler velocity log  
 DWA dynamic window approach

---

**E**


---

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

---

**F**


---

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

---

**G**


---

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

GDP	gross domestic product	IA	instantaneous allocation
GenoM	generator of modules	IAD	intelligent assist device
GEO	geostationary Earth orbit	ICA	independent component analysis
GI	gastrointestinal	ICBL	International Campaign to Ban Landmines
GICHD	Geneva International Center for Humanitarian Demining	ICE	internet communications engine
GJM	generalized Jacobian matrix	ICP	iterative closest-point algorithm
GLS	Global Navigation Satellite System Landing System	ICR	instantaneous center of rotation
GMM	Gaussian mixture model	ICRA	International Conference on Robotics and Automation
GMR	Gaussian mixture regression	ICT	information and communication technology
GNS	global navigation systems	IDL	interface definition language
GNSS	global navigation satellite system	IE	information ethics
GP	Gaussian processes	IED	improvised explosive device
GPR	ground-penetrating radar	IEEE	Institute of Electrical and Electronics Engineers
GPRS	general packet radio service	IETF	Internet engineering task force
GPS	global positioning system	IFRR	International Foundation of Robotics Research
GRACE	graduate robot attending conference	iGPS	indoor GPS
GSD	geon structural description	IHIP	intermediate haptic interaction points
GSI	Gadd's severity index	IK	inverse kinematics
GUI	graphical user interface	ILP	inductive logic programming
GZMP	generalized ZMP	ILS	instrument landing system
<b>H</b>		IMTS	intelligent multimode transit system
HAL	hybrid assisted limb	IMU	inertial measurement units
HAMMER	hierarchical attentive multiple models for execution and recognition	IOSS	input-output-to-state stability
HCI	human computer interaction	IP	internet protocol
HD	haptic device	IPC	interprocess communication
HDSL	high data rate digital subscriber line	ISO	International Organization for Standardization
HEPA	semi-high efficiency-particulate airfilter	ISP	internet service provider
HF	hard-finger	ISS	input-to-state stability
HIC	head injury criterion	IST	Information Society Technologies
HIP	haptic interaction point	IST	Instituto Superior Técnico
HJB	Hamilton–Jacobi–Bellman	IT	intrinsic tactile
HJI	Hamilton–Jacobi–Isaac	IT	inferotemporal
HMD	head-mounted display	ITD	interaural time difference
HMM	hidden Markov model	IxTeT	indexed time table
HMX	high melting point explosives	<b>J</b>	
HO	human operator	JAUS	joint architecture for unmanned systems
HRI	human–robot interaction	JAXA	Japan space exploration agency
HRTEM	high-resolution transmission electron microscopes	JDL	joint directors of the laboratories
HST	Hubble space telescope	JEMRMS	Japanese experiment module remote manipulator system
HSTAMIDS	handheld standoff mine detection system	JHU	Johns Hopkins University
HTML	hypertext markup language	JND	just noticeable difference
HTN	hierarchical task network	JPL	Jet Propulsion Laboratory
<b>I</b>		JSIM	joint-space inertia matrix
I/O	input/output	JSP	Java Server Pages
I3CON	industrialized, integrated, intelligent, construction		

**K**

KR knowledge representation

**L**

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

**M**

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

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

**N**

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

**O**

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

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

---

**P**


---

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

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

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**Q**


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QD	quantum dot
QRIO	quest for curiosity
QT	quasistatic telerobotics

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**R**


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

RT reaction time  
 RT room-temperature  
 RTCA Radio Technical Commission for  
 Aeronautics  
 RTD resistance temperature device  
 RTI real-time innovations  
 RTK real-time kinematics  
 RTS real-time system  
 RWI real-world interface  
 RWS robotic work station

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**S**


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

SPDM special-purpose dexterous manipulator  
 SPS standard position system  
 SR single-robot  
 SRMS shuttle remote manipulator system  
 SSRMS Space shuttle remote manipulator  
 system  
 ST single-task  
 STM scanning tunneling microscopes  
 STS superior temporal sulcus  
 SVD singular value decomposition  
 SWNT single-walled carbon nanotubes

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**T**


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

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**U**


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

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**V**


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



vdW	van der Waals
VFH	vector field histogram
VI	value iteration
VIA	variable-impedance actuation
VLSI	very-large-scale integrated
VM	virtual manipulator
VO	velocity obstacles
VOR	vestibular-ocular reflex
VOR	VHF omnidirectional range
VR	virtual reality
VRML	virtual reality modeling language
VVV	versatile volumetric vision

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**W**

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WABIAN	Waseda bipedal humanoid
WAM	whole-arm manipulator

WAN	wide-area network
WG	world graph
WMR	wheeled mobile robot
WMSD	work-related musculoskeletal disorders
WTA	winner-take-all
WWW	world wide web

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**X**

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XHTML	extensible hyper text markup language
XML	extensible markup language

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**Z**

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ZMP	zero-moment point
ZP	zona pellucida