

# Introduction

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Robots! Robots on Mars and in oceans, in hospitals and homes, in factories and schools; robots fighting fires, making goods and products, saving time and lives . . . Robots today are making a considerable impact on many aspects of modern life, from industrial manufacturing to healthcare, transportation, and exploration of the deep space and sea. Tomorrow, robots will be as pervasive and personal as today's personal computers. The dream to create machines that are skilled and intelligent has been part of humanity from the beginning of time. This dream is now becoming part of our world's striking reality.

Since the early civilizations, one of man's greatest ambitions has been to create artifacts in their image. The legend of the Titan Prometheus, who molded humankind from clay, or that of the giant Talus, the bronze slave forged by Hephaestus (3500 BC), testify to this quest in Greek mythology. The Egyptians' oracle statues hiding priests inside (2500 BC) were perhaps the precursor of our modern thinking machines. The clepsydra water clock introduced by the Babylonians (1400 BC) was one of the first automated mechanical artifacts. In the following centuries, human creativity has given rise to a host of devices such as the automaton theatre of Hero of Alexandria (100 AD), the hydro-powered water-raising and humanoid machines of Al-Jazari (1200), and Leonardo da Vinci's numerous ingenious designs (1500). The development of automata continued to flourish in the eighteenth century both in Europe and Asia, with creations such as Jacquet-Droz's family of androids (drawer, musician and writer) and the "karakuri-ningyo" mechanical dolls (tea server and archer).

The robot "concept" was clearly established by those many creative historical realizations. Nonetheless, the emergence of the "physical" robot had to await the advent of its underlying technologies during the course of the twentieth century. In 1920, the term *robot* – derived from "robota" which means subordinate labour in Slav languages – was first introduced by the Czech playwright Karel Čapek in his play "Rossum's Universal Robots (R.U.R.)". In 1940, the ethics of the interaction

between robots and humans was envisioned to be governed by the well-known three fundamental laws of Isaac Asimov, the Russian science-fiction writer in his novel "Runaround".

The middle of the twentieth century brought the first explorations of the connection between human intelligence and machines, marking the beginning of an era of fertile research in the field of artificial intelligence (AI). Around that time, the first robots were realized. They benefited from advances in the different technologies of mechanics, controls, computers and electronics. As always, new designs motivate new research and discoveries, which, in turn, lead to enhanced solutions and thus to novel concepts. This virtuous circle over time produced that knowledge and understanding which gave birth to the field of *robotics*, properly referred to as: the science and technology of robots.

The early robots built in the 1960s stemmed from the confluence of two technologies: numerical control machines for precise manufacturing, and teleoperators for remote radioactive material handling. These master-slave arms were designed to duplicate one-to-one the mechanics of the human arm, and had rudimentary control and little perception about the environment. Then, during the mid-to-late twentieth century, the development of integrated circuits, digital computers and miniaturized components enabled computer-controlled robots to be designed and programmed. These robots, termed industrial robots, became essential components in the automation of flexible manufacturing systems in the late 1970s. Further to their wide application in the automotive industry, industrial robots were successfully employed in general industry, such as the metal products, the chemical, the electronics and the food industries. More recently, robots have found new applications outside the factories, in areas such as cleaning, search and rescue, underwater, space, and medical applications.

In the 1980s robotics was defined as the science which studies the *intelligent connection between perception and action*. With reference to this definition, the action of a robotic system is entrusted to a *locomotion*

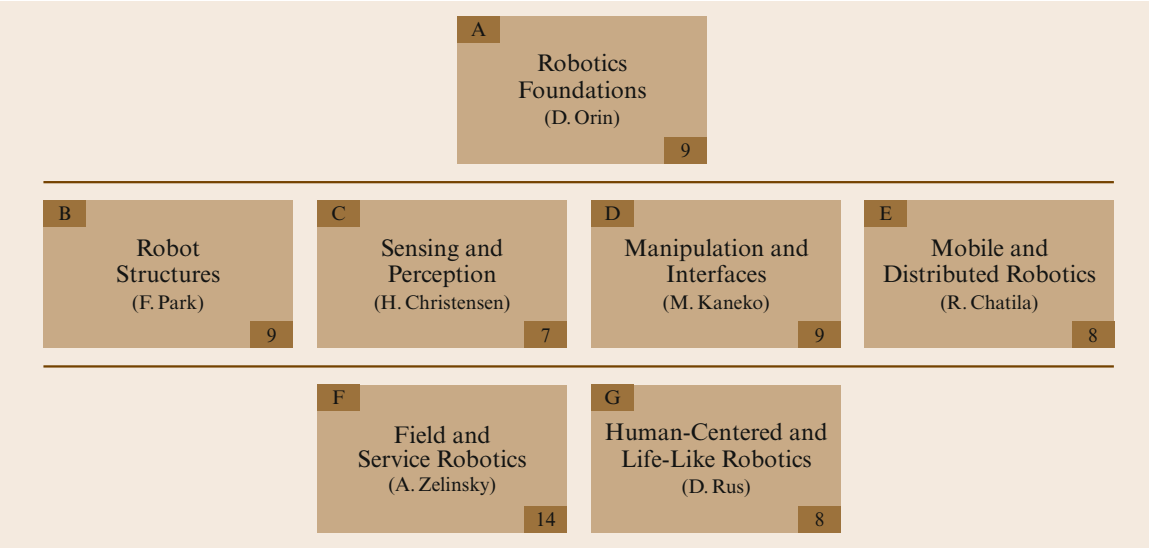


Fig. 1 Organization of the handbook

apparatus to move in the environment (wheels, crawlers, legs, propellers) and/or to a *manipulation* apparatus to operate on objects present in the environment (arms, end effectors, artificial hands), where suitable *actuators* animate the mechanical components of the robot. The perception is extracted from the *sensors* providing information on state of the robot (position and speed) and its surrounding environment (force and tactile, range and vision). The intelligent connection is entrusted to a *programming, planning and control* architecture which relies on the perception and available *models* of the robot and environment and exploits learning and skill acquisition.

In the 1990s research was boosted by the need to resort to robots to address human safety in hazardous environments (*field robotics*), or to enhance the human operator ability and reduce his/her fatigue (*human augmentation*), or else by the desire to develop products with wide potential markets aimed at improving the quality of life (*service robotics*). A common denominator of such application scenarios was the need to operate in a scarcely structured environment which ultimately requires increased abilities and a higher degree of *autonomy*.

By the dawn of the new millennium, robotics has undergone a major transformation in scope and dimensions. This expansion has been brought about by the maturity of the field and the advances in its related technologies. From a largely dominant industrial focus, robotics has been rapidly expanding into the

challenges of the human world (*human-centered and life-like robotics*). The new generation of robots is expected to safely and dependably co-habitat with humans in homes, workplaces, and communities, providing support in services, entertainment, education, healthcare, manufacturing, and assistance.

Beyond its impact on physical robots, the body of knowledge robotics has produced is revealing a much wider range of applications reaching across diverse research areas and scientific disciplines, such as: biomechanics, haptics, neurosciences, virtual simulation, animation, surgery, and sensor networks among others. In return, the challenges of the new emerging areas are proving an abundant source of stimulation and insights for the field of robotics. It is indeed at the intersection of disciplines that the most striking advances happen.

Today, new communities of users and developers are forming, with growing connections to the core of robotics research. A strategic goal for the robotics community is one of outreach and scientific cooperation with these communities. Future developments and expected growth of the field will largely depend on the research community's abilities to achieve this objective.

The dissemination of research results and findings in archival publications and conference presentations has played an important role in the advancement of robotics in the past decades. The extent of scientific activities in robotics has led to the establishment of professional societies and research networks devoted to the field.

The introduction of graduate programs in robotics in many academic institutions around the world is a clear illustration of the level of maturity reached by robotics as a scientific field.

The intensive stream of robotics research documented in the literature culminates into this unique reference, which aims at collecting in one self-contained volume the most significant achievements of our international robotics community. The *Springer Handbook of Robotics* presents a full coverage of the field from its foundations, through the research areas, up to the new emerging applications of robotics. Accordingly, the material is organized in three logical layers reflecting the historical development of the field, as illustrated in Fig. 1.

The foundations of robotics science, laid down in the first layer (Part A with its 9 chapters), address the theory of robot mechanics, sensing, planning, and control. The consolidated methodologies and technologies of robot structures (Part B with its 9 chapters), sensing and perception (Part C with its 7 chapters), manipulation and interfaces (Part D with its 8 chapters) and mobile and distributed robotics (Part E with its 8 chapters) are presented in the second layer. The third layer is devoted to advanced applications, such as in field and service robotics (Part F with its 14 chapters) and human-centered and life-like robotics (Part G with its 9 chapters).

**Part A** presents the fundamental principles and methods that are used to model, design, and control a robotic system. All of the foundational topics are included in this part: kinematics, dynamics, mechanical design and actuation, sensing and estimation, motion planning, motion control, force control, robotic systems architectures and programming, and **AI** reasoning methods for task planning and learning. A chapter is devoted to each of these topics. The topics are expanded and applied to specific robotic structures and systems in subsequent parts.

**Part B** is concerned with the design, modeling, motion planning, and control of the actual physical realizations of a robot. Some of the more obvious mechanical structures that come to mind are arms, legs, and hands; to this list can be added wheeled vehicles and platforms, and robot structures at the micro and nano scales. With separate chapters devoted to performance criteria and model identification, the chapters in this part successively examine serial redundant mechanisms, parallel

mechanisms, flexible robots, robot hands, robot legs, wheeled robots, and micro and nano-scale robots.

**Part C** covers different sensory modalities and integration of sensor data across space and time to generate models of robots and the external environment. Robotics is the intelligent coupling of perception and action and as such Part C complements Part B to build systems. This part of the handbook covers sensing across contact, proprioception to exteroception. The main sensor types such as tactile, odometry, **GPS**, ranging and visual perception are presented. Both basic sensor models, sensor data processing and associated representations are covered. Finally, a chapter on sensor fusion introduces the mathematical tools needed for integration of sensor information across space and time.

**Part D** is concerned with interaction between robots and objects, or between humans and robots. Manipulation is supposed to handle an object through direct contact by arms or fingers or just a pusher, while interfaces are supposed to make either direct or indirect interaction between humans and robots. For enhancing dexterity in robot manipulation, motion for manipulation tasks, contact modeling and manipulation, grasping, and cooperative manipulators are addressed in the first half of this part. For achieving a skillful manipulation or power increase in a human/robot system, haptics, telerobotics, networked telerobotics, and exoskeletons for human performance augmentation are discussed in the second half of part D.

**Part E** covers a wide span of topics. This part addresses motion planning and control of wheeled robots with kinematic constraints, perception and world modeling, simultaneous localization and mapping, and the integration of those capacities in a control architecture, as a mobile robot is actually the paradigm of a complex integrated system. This part completes Part A on foundations in the context of mobile robotics, and given the role of perception, is closely related to Part C on sensing. In addition, multi-robot interaction and systems are also discussed, including modular and reconfigurable robots as well as networked robotics.

**Part F** covers topics related to creating field and service application-based robots that operate in all types of environments. This includes applications ranging from industrial robots, through a diverse array of air, land, sea and space applications to educational robotics. This part

of the handbook, which draws on Parts A, B, C, D and E, describes how robots can be put to work.

**Part G** covers topics related to creating robots that operate in human-centered environments. This includes the design of robots with humanoid and other biologically inspired morphologies, sensors, actuators, and control architectures. User interfaces, such as programming by demonstration and programming for safety, are also included in this part, and it concludes with the socio-ethical implications of robots.

The handbook was conceived to provide a valuable resource not only for robotics experts, but also for newcomers to this expanding field (engineers, medical doctors, computer scientists, and designers). In particular, it is important to underline the tutorial value of Part A to graduate students and post-docs, the research value of Parts B to E for a wider coverage of research in robotics, and the added value of Parts F and G to engineers and scientists interested in new applications.

The contents of the various chapters have been inspired by a classic cut, i.e. avoiding the inclusion of on-going or not well-established methods. An objective perspective has been taken, while covering multiple approaches, with the goal of ensuring a high archival value to the handbook. Each chapter is preceded by a short summary, and an introductory section providing the state of the art in the area. The core sections are developed at a tutorial level. Lengthy mathematical derivations have been avoided whenever possible, while the equations, tables, and algorithms are illustrated in ready-to-use form. The final section of the chapter provides conclusions and topics for further reading.

From the foundations to the social and ethical implications of robotics, the sixty-four chapters of the handbook provide a comprehensive collection of five decades of progress in robotics. This sum is a testimony to the level of accomplishments in our field, and a premise of further advances towards new frontiers of robotics.