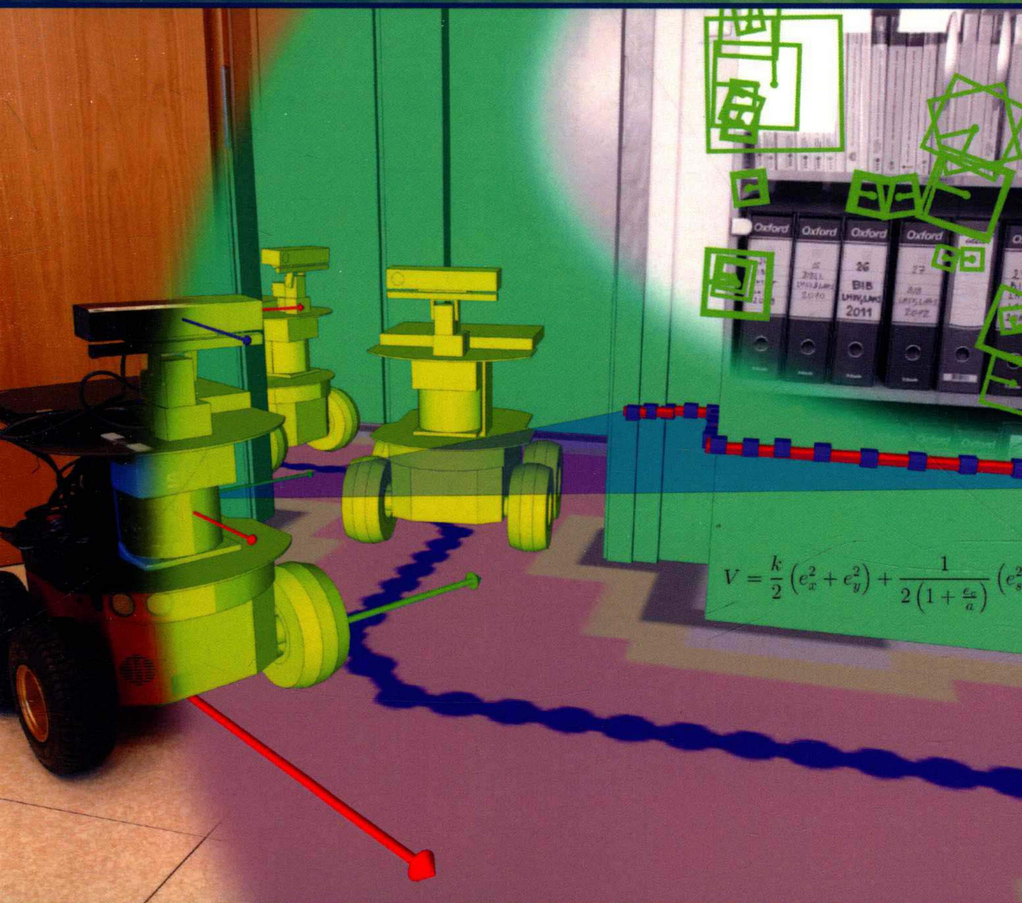
WHEELED MOBILE ROBOTICS

FROM FUNDAMENTALS TOWARDS AUTONOMOUS SYSTEMS



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MATLAB® examples

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WHEELED MOBILE ROBOTICS

PREFACE

This is an introductory book on the subject of wheeled mobile robotics, covering all the essential knowledge and algorithms that are required in order to achieve autonomous capabilities of mobile robots. The book can serve both as a textbook for engineering students and a reference book for professionals in the field. As a textbook, it is suitable for courses in mobile robotics, especially if the courses' main emphasis is on mobile robots with wheels. The book covers topics from mathematical modeling of motion, sensors and measurements, control algorithms, path planning, nondeterministic events, and state estimation. The theory is supported with examples that have solutions and excerpts of Matlab code listings in order to make it simple for the reader to try, evaluate, and modify the algorithms. Furthermore, at the end of the book some interesting practical projects are depicted, which can be used for laboratory practice or to consolidate the theory learned.

The field of autonomous mobile robotics is an extremely popular field of research and development. Within this field the majority of mobile robots use wheels for motion. Wheeled mobile robots leave tracks where no man has ever been (e.g., extraterrestrial explorations), man should not go (e.g., dangerous or contaminated areas), or act alongside humans (e.g., human support and assistance). Wheeled mobile robots have already started to penetrate into our homes in the form of robotic floor cleaners and lawn mowers, automatic guided vehicles can be found inside many industrial facilities, prototype self-driving cars already drive in the normal traffic, and in the nearby future many new applications of autonomous wheeled mobile robots are expected to appear, even in some unforeseen ways. The purpose of this book is to shed some light onto the design and give a deeper insight into the algorithms that are required in order to implement autonomous capabilities of wheeled mobile robots. The book addresses essential problems in wheeled mobile robotics and presents to the reader various approaches that can be used to tackle them. The presented algorithms range from basic and simple solutions to more advanced and state-of-the-art approaches.

The complete Matlab code listings of the algorithms that are presented in this book are also available for download at the book companion website: http://booksite.elsevier.com/9780128042045/. Therefore it should be simple for the readers to try, evaluate, tweak and tune the algorithms by themselves. The website also contains many animated videos from the examples that give an additional insight into the topics and algorithms covered in the book.

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CHAPTER 1

Introduction to Mobile Robotics

1.1 INTRODUCTION

1.1.1 Robots

The word *robot* has roots in Slavic languages. The meaning of "*robota*" in Polish is work or labor, while the word is more archaic in Czech or Slovenian language and means statute labor or corvée. The famous Czech writer Karel Čapek coined the word robot and used it in the science fiction play *R.U.R.*, which stands for Rossum's Universal Robots. The robots in the play are a sort of artificial human; in modern terminology cyborgs or androids would be more appropriate. The play witnessed huge success and the word robot was adopted by the majority of world languages. While the word robot is not even 100 years old, the idea of mechanic creatures goes very deep into history.

In Greek mythology we find many creatures that are used for particular tasks. Spartoi are mythical, fierce, and armed men who sprang up from the dragon's teeth sown by Cadmus. They assisted Cadmus in building the Cadmeia or citadel of Thebes. Talos, created by Hephaestus, was a giant automaton made of bronze to protect Europa in Crete from pirates and invaders. The Greek god of blacksmiths and craftsmen, Hephaestus, is also credited for some other mechanical structures. Automata can be also found in ancient Jewish, Chinese, and Indian legends. The idea of mechanical automata that resembled either humans or animals was then present in literature throughout the history. It really became popular in the 19th century and, especially, the 20th century. In the 20th century robots found a new popular media to depict them and bring them to life: film. Some of the ideas in literature and films were attributed as science fiction at the time of creation, and later this fiction became a reality.

The robotic designs were not present only in fiction. Very early inventors tried to construct mechanical automata. The Greek mathematician

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Fig. 1.1 Model of a bicycle and a programmable cart built based on Leonardo da Vinci's notes.

Archytas is believed to have designed and built the first artificial, self-propelled flying device in the 4th century BC. A mechanical bird propelled by steam was said to have actually flown some 200 m. In the comprehensive heritage of Leonardo da Vinci several mechanical designs can be found. Among the rough sketches scattered throughout Leonardo's notes, Rosheim [1] has reconstructed a programmable cart (Fig. 1.1) used as a base for Leonardo's inventions, such as a robot lion and a robot knight. The spring of industrial revolution technological advancement resulted in the outburst of automation that gradually led to the mobile robotics we know today.

1.1.2 Mobile

The word *mobile* has its roots in the Latin word of the same meaning, "*mōbilis*." The majority of animal species possess the ability of locomotion. While some animals use passive systems to do so (they can move with water or air motion), others have developed more or less sophisticated mechanisms for active movement. Some animals perform locomotion in the 3D space (swimming in the water, flying in the air, moving through the soil), and others more or less follow the 2D surface of the water or the ground, while some animals are capable of combining different ways of movement. In the context of mobile robots we are concerned with systems that can move using their locomotion apparatus. The latter very often mimics the one of a human or a certain animal. Copying from biological

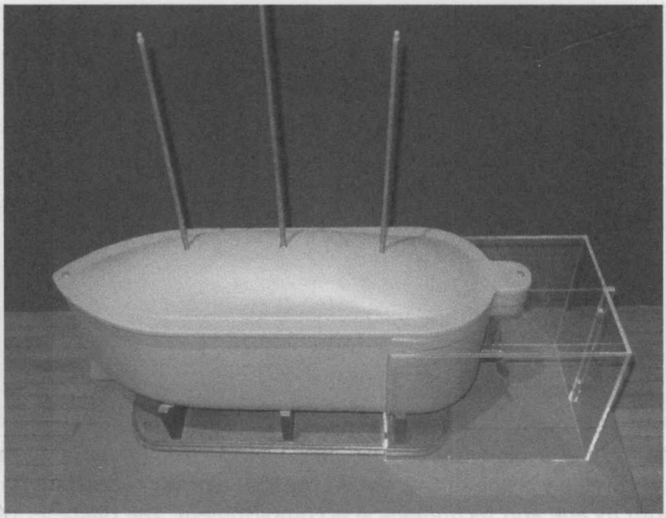

Fig. 1.2 A working replica of the radio-controlled electrical boat built by Nikola Tesla.

systems also very often successfully solves some technical problems that arise during artificial locomotion system design.

The other important aspect of a mobile system is that being mobile also means that the distance to the human operator can become large. This implies that the system needs to either possess a certain level of autonomy, meaning that it has to move across the space without the help of the operator, or accept the commands from a distant operator, meaning that the system is able to move tele-operated. Nikola Tesla was the first to design and build a radio-controlled electrical boat (Fig. 1.2) at the end of the 19th century. In the 20th and the 21st century the level of autonomy continuously rose. Yet, all the existing mobile systems are human operated on a certain level.

1.1.3 Wheels

Although very primitive animal species are able to move, it is often a nontrivial task to design an artificial system that is able to mimic animal locomotion. While wheels or similar structures cannot be found in the animal world, the vehicles with wheels are known to enable energy-efficient motion over the ground. The surface has to be smooth enough although appropriately constructed wheeled vehicles can also move over rugged terrain, such as steps. It is not known where and when the wheel

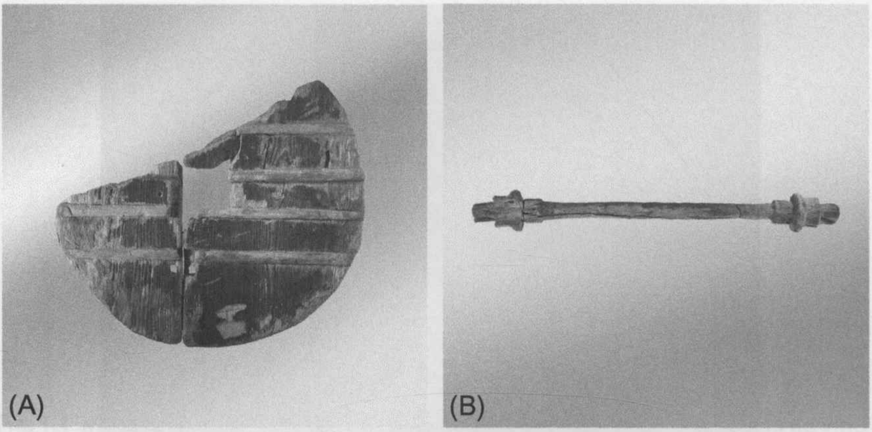

Fig. 1.3 The 5200-year-old wooden wheel (A) with the axle (B) found in the Ljubljana Marshes pile dwelling is one of the world's most significant cultural heritage items in terms of both its age and technological accomplishment. The diameter of the wheel is 70 cm and the axle length is 120 cm. *(Museum and Galleries of Ljubljana, photos by M. Paternoster.)*

was invented but the established belief is that the first wheels were used in Mesopotamia approximately 4000 BC. From there, they were spread around the world. Some experts attribute the wheel's invention to prehistoric Europe. The oldest wooden wheel with an axle, 5200 years old, was discovered in Slovenia in the Ljubljana Marshes (Fig. 1.3).

1.1.4 Autonomous Mobile Systems

Mobile systems can be defined as systems that are not attached to the environment and can move in a certain space. In terms of the environment they move across they can be classified into some principal groups:

Ground mobile systems Various types of mobile platforms can be found here such as mobile vehicles with wheels or caterpillars, legged robots (humanoids or animal mimicking), or robots that mimic some other type of animal locomotion, for example, snakes. Ground mobile systems with wheels or caterpillars that do not carry the operator are often referred to as unmanned ground vehicles.

Aerial mobile systems This group consists of mobile systems that fly in a certain aerial space (airplanes, helicopters, drones, rockets, animal-mimicking flying systems; when used without a pilot they are referred to as unmanned aerial vehicles) or orbit the Earth or some other celestial body (satellites).

Water and underwater mobile systems In this group we find different types of ships, boats, submarines, autonomous underwater vehicles, etc.

In this book only the wheeled mobile vehicles will be discussed although a large portion of the presented material can be used for other types of mobile systems with appropriate modifications.

Mobile systems are regarded as autonomous when they are capable of autonomous motion within their environment. Autonomy has to be guaranteed by the following:

- from the energy point of view: the robot should carry some source of energy; and
- from the decision point of view: the robot should be capable of taking certain decisions and performing appropriate actions.

In reality this means that the mobile system takes the commands from the human operator based on the level of autonomy the system is capable of. The system responds by trying to carry out the commanded task and appropriate subtasks on the lower levels. In case there are no unforeseen circumstances, the task is usually executed in a certain time interval. Based on the level of the robot's autonomy, the following typical commands can be taken from the operator:

Desired wheel velocities The robot takes the commands in terms of its wheel velocities and very basic control algorithms with appropriate sensors (typically rotary encoders) to ensure that the wheels rotate as commanded.

Desired robot longitudinal and angular velocities The computer program running on the robot is aware of the robot's kinematic model, so that it can compute the appropriate wheel velocities to achieve the desired robot velocities.

Desired robot path or robot trajectory The robot is capable of determining and controlling its pose within its environment; the pose is usually defined as joint information about position and orientation relative to some coordinate system. On this level we find robot localization that uses different sensors mounted either on the robot or in the environment to obtain the best possible approximation of the robot's pose. The problems also arise in control due to nonlinear character of the system, erroneous sensor information, wheel slipping, poor models, delays, etc.

Desired operation inside of the known environment with potential obstacles The robot has to perform an operation in the known environment but with some (static or moving) obstacles. On this level the robot is capable of planning its path and replanning it if some obstacles prevent the fulfillment of the operation.

Desired operation inside of the unknown environment The robot does not know its environment. It has to simultaneously perform the actions of determining its pose and building its map of environment; the approach is known as SLAM (simultaneous localization and mapping).

Desired mission The robot starts the mission that it has to accomplish. It operates in the environment where it might cooperate with other robots or agents. It needs to have a certain understanding of its missions. It needs to have certain priorities of its missions, so that it can abort a certain mission and/or take a mission with a higher priority. A lot of decision making has to be built in the robot. A simple example is that the robot needs to inspect the energy level in batteries and has to recharge its batteries if necessary.

The robots are not understood as autonomous on the first two levels shown above. Also, there exist other classifications. It is important that we understand the tasks and intelligence that the robot possesses on a certain level.

The main mechanical and electronic parts of an autonomous mobile robot are the following:

Mechanical parts Rigid and moving parts (body, wheels, tracks, legs, etc.)
Actuators Electrical motors (DC, stepper, servomotor, etc.)
Sensors Rotation encoders, proximity and distance sensors, inertial navigation unit, global navigation satellite system, etc.
Computers Micro-controllers, portable personal computer, embedded systems, etc.
Power unit Batteries, solar panels, etc.
Electronics Actuator drive, sensor measurement, power distribution, and telecommunication electronics

This book is about algorithms that are required to process sensor data and drive the actuators in order to give autonomous capabilities to the mobile robot.

There are several properties that make use of wheeled mobile robots appealing. Mobile robots allow human-free access to hazardous environments (e.g., minefields, radioactive environments, deep-sea explorations, etc.) and access to remote or inaccessible environments (e.g., exploration of extraterrestrial planets, nanoscale robots in medicine, etc.). Robotic systems can do physically demanding tasks instead of humans. The introduction of automation, robotics, and mobile systems also allows for greater productivity, product or service quality, and can reduce labor costs.

Nowadays, mobile systems are used in numerous applications in different fields, which are constantly expanding due to rapid technological development. An incomplete list of applications of wheeled mobile robots includes the following:

- medical services, operation support, laboratory analyses (e.g., in situations with the risk of infections)
- cleaning applications (floor vacuuming, sweeping and mopping in homes or large buildings, window cleaning, etc.)
- applications in agriculture, like automated fruit picking, seed planting, grass mowing, etc.
- forest maintenance and logging
- consumer goods stores
- inspection and surveillance of hazardous areas (detection and deactivation of mines in minefields, review of nuclear reactors, cleaning of sewer pipes)

- space missions (satellites, inspection and servicing of satellites, planetary exploration)
- depths of the sea (robots for cabling and screening the seabed)
- robots for loading and unloading goods or materials from airplanes, ships, or trucks
- military robots (reconnaissance robots, airplanes, and various autonomous projectiles)
- security robots (security guards to control storage, buildings, etc.)
- help for the elderly and disabled (autonomous wheelchairs, rehabilitation robots)
- consumer applications (robotic pets, robot soccer, etc.)
- systems at research institutions aimed at learning and developing new algorithms

Predicting the way the future will look like has always been a hard task. Technologies and applications that are available today, were hard to imagine even a decade ago. However, in the near future autonomous wheeled mobile robots are expected to become an even more integral part of our daily lives: they will work alongside us in modern factories of the future, help us with domestic chores, drive us on the road, save lives in rescue missions and much more. How technological development brought us to current point is depicted in a short history review in the next section.

1.2 HISTORY

This section presents some important milestones in the history of wheeled mobile robotics [2]. Focus is given to the application of wheeled mobile robots; however, some other technological achievements that influenced the field are mentioned.

1898 At an electrical exhibition at Madison Square Garden in New York City, Nikola Tesla demonstrated a radio-controlled unmanned boat [3]. Nikola Tesla holds a patent [4] for the invention.

1939–45 During World War II, cruise missiles V-1 [5] and V-2 [6] were developed in Germany. At the same time an American, Norbert Wiener, was working on automatic aiming of antiaircraft guns [7].

1948–49 W. Grey Walter constructed two autonomous robots, Elmer and Elsie [8], which resembled turtles and were capable of following a light source (photodiode), detecting obstacles (contact switch), and preventing collisions.

1961–63 Johns Hopkins University developed *Beast* [9], a self-surviving mobile robot that was able to wander through white halls, seeking black wall outlets to recharge its batteries.

1966–72 The Stanford Research Institute was developing Shakey the robot [10], which had a camera, sonar range finders, collision detection sensors, and a wireless link. It was the first general-purpose mobile robot capable of sensing and interpreting the environment, and then navigating between the obstacles on its own. Results of the project include development of A* search algorithm, Hough transform, and visibility graph.

1969 A first robotic lawn mower, MowBot, was introduced and patented [11].

1970 The Soviet Union successfully landed the first lunar rover Lunokhod 1 on the Moon's surface, which was remote controlled from the Earth and it carried several cameras and other sensors. In 301 days of operation the rover traveled approximately 10 km, returned more than 25,000 images, and made several soil analyses [12].

1973 The Soviet Union deployed a second lunar rover Lunokhod 2 on the surface of the Moon. During the 4-month mission the rover covered a distance of 39 km, a record for off-Earth driving distance that lasted until 2014 [13].

1976 NASA unmanned spacecrafts Viking 1 and Viking 2 (each consisting of an orbiter and a lander) entered Mars' orbit, and the landers soft-landed on Mars' surface several days later [14].

1977 French Laboratory for Analysis and Architecture of Systems started developing mobile robot Hilare 1 [15], which was equipped with ultrasonic and laser range finders and a camera on a robotic arm.

1979 The Stanford Cart (initial model introduced in 1962) became capable of vision-based navigation through an obstacle course [16].

1982 A first model from the series of commercial HERO robots became available, which were mainly targeted for home and educational use [17].

1986 The team of Ernst Dieter Dickmanns [18] developed the robot car VaMoRs that was able to drive by itself on streets without traffic, reaching speeds up to 90 km/h.

1995 An affordable mobile robot, Pioneer, for education and research appeared on the market [19].