1 Introduction

1.1 Introduction

Robotics has achieved its greatest success to date in the world of industrial manufacturing. Robot arms, or *manipulators*, comprise a $ 2 billion industry. Bolted at its shoulder to a specific position in the assembly line, the robot arm can move with great speed and accuracy to perform repetitive tasks such as spot welding and painting (figure 1.1). In the electronics industry, manipulators place surface-mounted components with superhuman precision, making the portable telephone and laptop computer possible.

Yet, for all of their successes, these commercial robots suffer from a fundamental disadvantage: lack of mobility. A fixed manipulator has a limited range of motion that depends

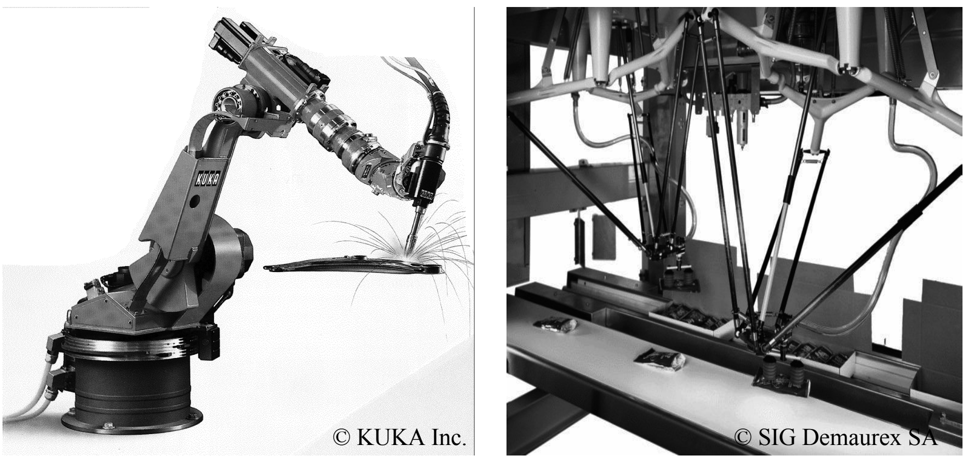


Figure 1.1
Picture of auto assembly plant-spot welding robot of KUKA and a parallel robot Delta of SIG Demaurex SA (invented at EPFL [305]) during packaging of chocolates.

on where it is bolted down. In contrast, a mobile robot would be able to travel throughout the manufacturing plant, flexibly applying its talents wherever it is most effective.

This book focuses on the technology of mobility: how can a mobile robot move unsupervised through real-world environments to fulfill its tasks? The first challenge is locomotion itself. How should a mobile robot move, and what is it about a particular locomotion mechanism that makes it superior to alternative locomotion mechanisms?

Hostile environments such as Mars trigger even more unusual locomotion mechanisms (figure 1.2). In dangerous and inhospitable environments, even on Earth, such *teleoperated* systems have gained popularity (figures 1.3-1.6). In these cases, the low-level complexities of the robot often make it impossible for a human operator to control its motions directly. The human performs localization and cognition activities but relies on the robot's control scheme to provide motion control.

For example, Plustech's walking robot provides automatic leg coordination while the human operator chooses an overall direction of travel (figure 1.3). Figure 1.6 depicts an underwater vehicle that controls three propellers to stabilize the robot submarine autonomously in spite of underwater turbulence and water currents while the operator chooses position goals for the submarine to achieve.

Other commercial robots operate not where humans *cannot* go, but rather share space with humans in human environments (figure 1.7). These robots are compelling not for reasons of mobility but because of their *autonomy*, and so their ability to maintain a sense of position and to navigate without human intervention is paramount.

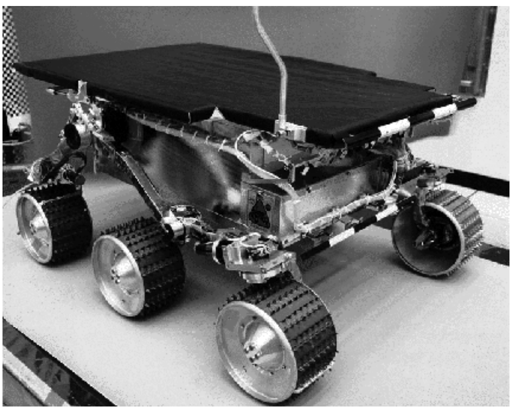


Figure 1.2
The mobile robot Sojourner was used during the Pathfinder mission to explore Mars in summer 1997. It was almost completely teleoperated from Earth. However, some on-board sensors allowed for obstacle detection (http://ranier.oact.hq.nasa.gov/telerobotics_page/telerobotics.shtm).
© NASA/JPL.

Figure 1.3
Plustech developed the first application-driven walking robot. It is designed to move wood out of the forest. The leg coordination is automated, but navigation is still done by the human operator on the robot. (http://www.plustech.fi). © Plustech.

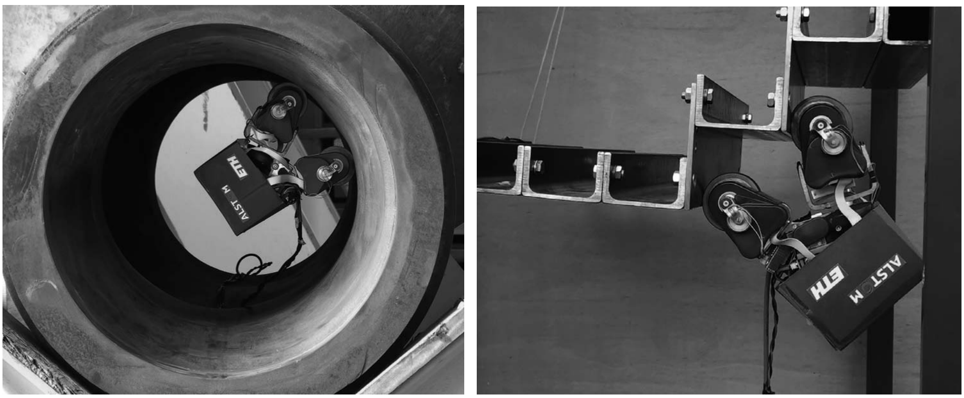


Figure 1.4
The MagneBike robot developed by ASL (ETH Zurich) and ALSTOM. MagneBike is a magnetic wheeled robot with high mobility for inspecting complex shaped structures such as ferromagnetic pipes and turbines (http://www.asl.ethz.ch/). © ALSTOM / ETH Zurich.

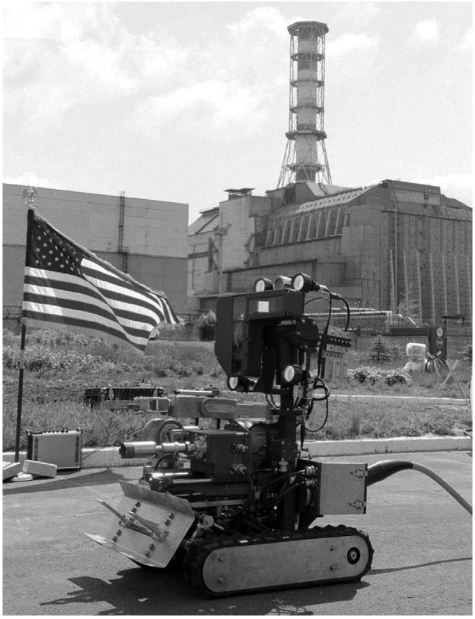


Figure 1.5
Picture of Pioneer, a robot designed to explore the Sarcophagus at Chernobyl. © Wide World Photos.

Figure 1.6
The autonomous underwater vehicle (AUV) Sirius being retrieved after a mission aboard the RV Southern Surveyor © Robin Beaman—James Cook University.

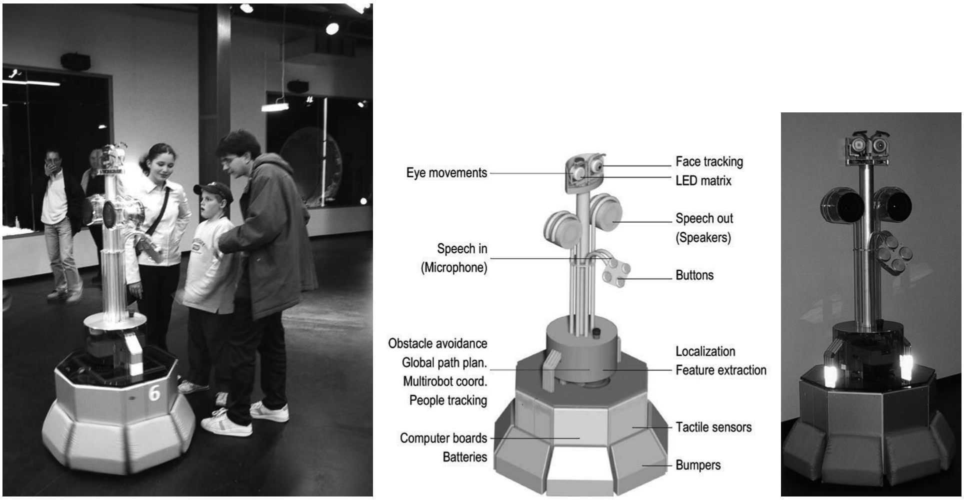
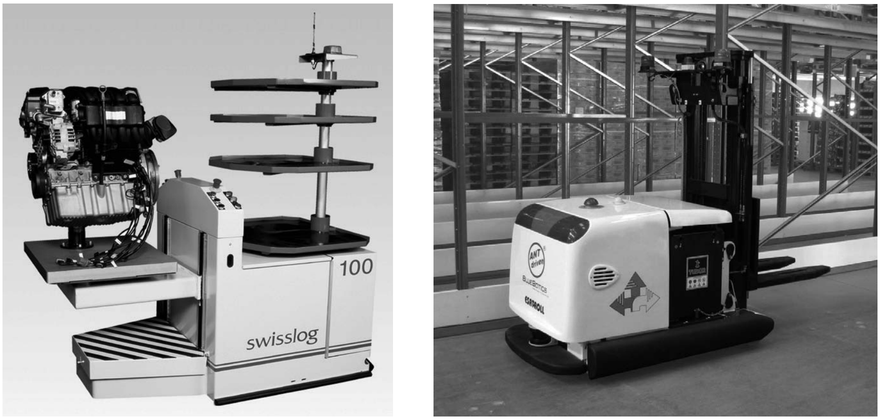


Figure 1.7
Tour-guide robots are able to interact and present exhibitions in an educational way [85, 251, 288, 310,]. Ten Roboxes have operated during five months at the Swiss exhibition EXPO.02, meeting hundreds of thousands of visitors. They were developed by EPFL [288] (http://robotics.epfl.ch) and commercialized by BlueBotics (http://www.bluebotics.com).

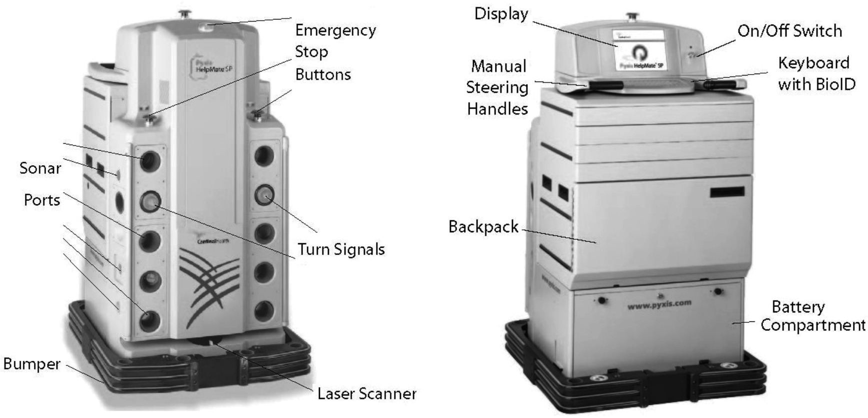
For example, AGV (autonomous guided vehicle) robots (figure 1.8) autonomously deliver parts between various assembly stations by following special electrical guidewires installed in the floor (figure 1.8a) or, differently, by using onboard lasers to localize within a user-specified map (figure 1.8b). The Helpmate service robot transports food and medication throughout hospitals by tracking the position of ceiling lights, which are manually specified to the robot beforehand (figure 1.9). Several companies have developed autonomous cleaning robots, mainly for large buildings (figure 1.10). One such cleaning robot is in use at the Paris Metro. Other specialized cleaning robots take advantage of the regular geometric pattern of aisles in supermarkets to facilitate the localization and navigation tasks.

Research into high-level questions of cognition, localization, and navigation can be performed using standard research robot platforms that are tuned to the laboratory environment. This is one of the largest current markets for mobile robots. Various mobile robot platforms are available for programming, ranging in terms of size and terrain capability. Very popular research robots are the Pioneer, BIBA, and the *e-puck* (figures 1.11-1.13) and also very small robots like the Alice from EPFL (Swiss Federal Institute of Technology at Lausanne) (figure 1.14).



a) *b)*

Figure 1.8
(a) Autonomous guided vehicle (AGV) by SWISSLOG used to transport motor blocks from one assembly station to another. It is guided by an electrical wire installed in the floor. © Swisslog.
(b) Equipped with the Autonomous Navigation Technology (ANT) from BlueBotics, Paquito, the autonomous forklift by Esatroll, does not rely on electrical wires, magnetic plots, or reflectors, but rather uses the onboard safety lasers to localize itself with respect to the shape of the environment. Image courtesy of BlueBotics (http://www.bluebotics.com).



front *back*

Figure 1.9
HELPMATE is a mobile robot used in hospitals for transportation tasks. It has various on-board sensors for autonomous navigation in the corridors. The main sensor for localization is a camera looking to the ceiling. It can detect the lamps on the ceiling as references, or landmarks (http://www.pyxis.com). © Pyxis Corp.

a) b)

Figure 1.10
(a) The Robot40 is a consumer robot developed and sold by Cleanfix for cleaning large gymnasiums. The navigation system of Robo40 is based on a sophisticated sonar and infrared system (http://www.cleanfix.com). © Cleanfix. (b) The RoboCleaner RC 3000 covers badly soiled areas with a special driving strategy until it is really clean. Optical sensors measure the degree of pollution of the aspirated air (http://www.karcher.de). © Alfred Kärcher GmbH & Co.

Figure 1.11
PIONEER is a modular mobile robot offering various options like a gripper or an on-board camera. It is equipped with a sophisticated navigation library developed at SRI, Stanford, CA. Reprinted with permission from ActivMedia Robotics, http://www.MobileRobots.com.

Figure 1.12
BIBA is a very sophisticated mobile robot developed for research purposes and built by BlueBotics (http://www.bluebotics.com/). It has a large variety of sensors for high-performance navigation tasks.

Figure 1.13
The *e-puck* is an educational desktop mobile robot developed at the EPFL [226]. It is only about 70 mm in diameter. As extensions to the basic capabilities, various modules such as additional sensors, actuators, or computational power have been developed. In this picture, two example extensions are shown: (center) an omnidirectional camera and (right) an infrared distance scanner (http://www.e-puck.org/). © Ecole Polytechnique Fédérale de Lausanne (EPFL).

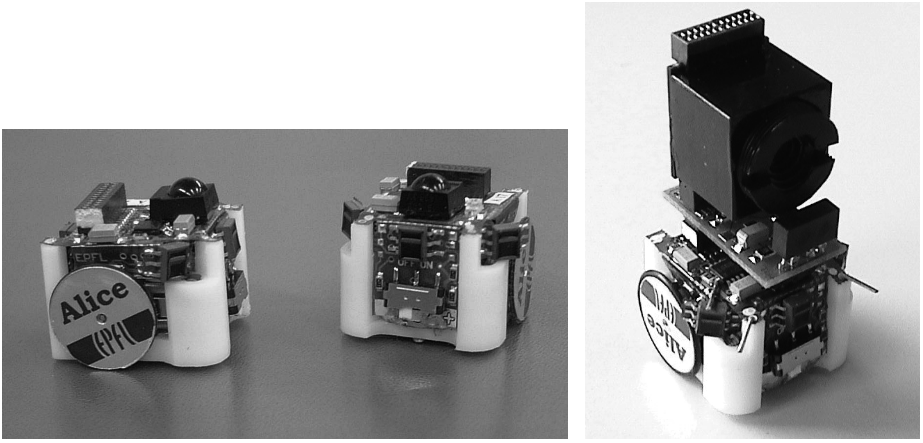


Figure 1.14
Alice is one of the smallest fully autonomous robots. It is approximately $2 \times 2 \times 2$ cm, it has an autonomy of about 8 hours and uses infrared distance sensors, tactile whiskers, or even a small camera for navigation [93].

Although mobile robots have a broad set of applications and markets as summarized above, there is one fact that is true of virtually every successful mobile robot: its design involves the integration of many different bodies of knowledge. No mean feat, this makes mobile robotics as interdisciplinary a field as there can be. To solve locomotion problems, the mobile roboticist must understand mechanism and kinematics, dynamics and control theory. To create robust perceptual systems, the mobile roboticist must leverage the fields of signal analysis and specialized bodies of knowledge such as computer vision to properly employ a multitude of sensor technologies. Localization and navigation demand knowledge of computer algorithms, information theory, artificial intelligence, and probability theory.

Figure 1.15 depicts an abstract control scheme for mobile robot systems that we will use throughout this text. This figure identifies many of the main bodies of knowledge associated with mobile robotics.

This book provides an introduction to all aspects of mobile robotics, including software and hardware design considerations, related technologies, and algorithmic techniques. The intended audience is broad, including both undergraduate and graduate students in introductory mobile robotics courses, as well as individuals fascinated by the field. Although it is not absolutely required, a familiarity with matrix algebra, calculus, probability theory, and computer programming will significantly enhance the reader's experience.

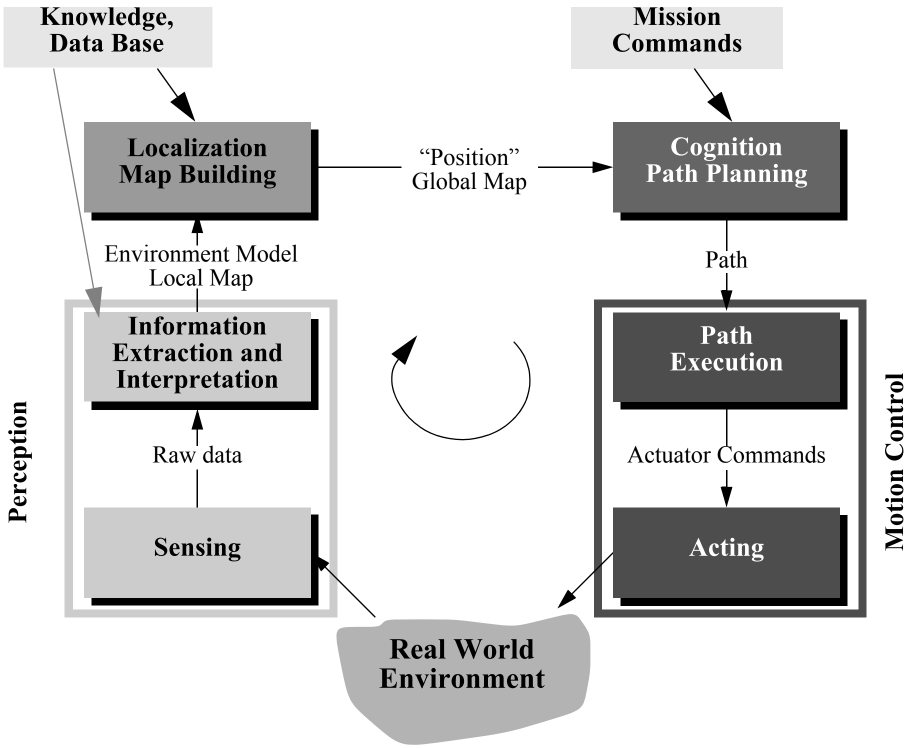


Figure 1.15
Reference control scheme for mobile robot systems used throughout this book.

Mobile robotics is a large field, and this book focuses not on robotics in general, or on mobile robot applications, but rather on mobility itself. From mechanism and perception to localization and navigation, this book focuses on the techniques and technologies that enable robust *mobility*.

Clearly, a useful, commercially viable mobile robot does more than just move. It polishes the supermarket floor, keeps guard in a factory, mows the golf course, provides tours in a museum, or provides guidance in a supermarket. The aspiring mobile roboticist will start with this book but will quickly graduate to coursework and research specific to the desired application, integrating techniques from fields as disparate as human-robot interaction, computer vision, and speech understanding.

1.2 An Overview of the Book

This book introduces the different aspects of a robot in modules, much like the modules shown in figure 1.15. Chapters 2 and 3 focus on the robot's low-level *locomotive ability*. Chapter 4 presents an in-depth view of *perception*. Chapters 5 and 6 take us to the higher-level challenges of *localization* and *mapping* and even higher-level *cognition*, specifically the *ability to navigate robustly*. Each chapter builds upon previous chapters, and so the reader is encouraged to start at the beginning, even if his or her interest is primarily at the high level. Robotics is peculiar in that solutions to high-level challenges are most meaningful only in the context of a solid understanding of the low-level details of the system.

Chapter 2, "Locomotion," begins with a survey of the most important mechanisms that enable locomotion: wheels, legs, and flight. Numerous robotic examples demonstrate the particular talents of each form of locomotion. But designing a robot's locomotive system properly requires the ability to evaluate its overall motion capabilities quantitatively. Chapter 3, "Mobile Robot Kinematics," applies principles of kinematics to the whole robot, beginning with the kinematic contribution of each wheel and graduating to an analysis of robot maneuverability enabled by each mobility mechanism configuration.

The greatest single shortcoming in conventional mobile robotics is, without doubt, perception: mobile robots can travel across much of earth's man-made surfaces, but they cannot perceive the world nearly as well as humans and other animals. Chapter 4, "Perception," begins a discussion of this challenge by presenting a clear language for describing the performance envelope of mobile robot sensors. With this language in hand, chapter 4 goes on to present many of the off-the-shelf sensors available to the mobile roboticist, describing their basic principles of operation as well as their performance limitations. The most promising sensor for the future of mobile robotics is vision, and chapter 4 includes an overview of the theory of camera image formation, omnidirectional vision, camera calibration, structure from stereovision, structure from motion, and visual odometry. But perception is more than sensing. Perception is also the *interpretation* of sensed data in meaningful ways. The second half of chapter 4 describes strategies for feature extraction that have been most useful in both computer vision and mobile robotics applications, including extraction of geometric shapes from range sensing data, as well as point features (such as Harris, SIFT, SURF, FAST, and so on) from camera images. Furthermore, a section is dedicated to the description of the most recent bag-of-feature approach that became popular for place recognition and image retrieval.

Armed with locomotion mechanisms and outfitted with hardware and software for perception, the mobile robot can move and perceive the world. The first point at which mobility and sensing must meet is localization: mobile robots often need to maintain a sense of position. Chapter 5, "Mobile Robot Localization," describes approaches that obviate the need for direct localization, then delves into fundamental ingredients of successful localization strategies: belief representation and map representation. Case studies demonstrate various localization schemes, including both Markov localization and Kalman filter localization. The final part of chapter 5 is devoted to a description of the Simultaneous Localization and Mapping (SLAM) problem along with a description of the most popular approaches to solve it such as extended-Kalman-filter SLAM, graph-based SLAM, particle filter SLAM, and the most recent monocular visual SLAM.

Mobile robotics is so young a discipline that it lacks a standardized architecture. There is as yet no established robot operating system. But the question of architecture is of paramount importance when one chooses to address the higher-level competences of a mobile robot: how does a mobile robot navigate robustly from place to place, interpreting data, and localizing and controlling its motion all the while? For this highest level of robot competence, which we term *navigation competence*, there are numerous mobile robots that showcase particular architectural strategies. Chapter 6, “Planning and Navigation,” surveys the state of the art of robot navigation, showing that today’s various techniques are quite similar, differing primarily in the manner in which they *decompose* the problem of robot control. But first, chapter 6 addresses two skills that a competent, navigating robot usually must demonstrate: obstacle avoidance and path planning.

There is far more to know about the cross-disciplinary field of mobile robotics than can be contained in a single book. We hope, though, that this broad introduction will place the reader in the context of the collective wisdom of mobile robotics. This is only the beginning. With luck, the first robot you program or build will have only good things to say about you.

2 Locomotion

2.1 Introduction

A mobile robot needs locomotion mechanisms that enable it to move unbounded throughout its environment. But there are a large variety of possible ways to move, and so the selection of a robot's approach to locomotion is an important aspect of mobile robot design. In the laboratory, there are research robots that can walk, jump, run, slide, skate, swim, fly, and, of course, roll. Most of these locomotion mechanisms have been inspired by their biological counterparts (see figure 2.1).

There is, however, one exception: the actively powered wheel is a human invention that achieves extremely high efficiency on flat ground. This mechanism is not completely foreign to biological systems. Our bipedal walking system can be approximated by a rolling polygon, with sides equal in length d to the span of the step (figure 2.2). As the step size decreases, the polygon approaches a circle or wheel. But nature did not develop a fully rotating, actively powered joint, which is the technology necessary for wheeled locomotion.

Biological systems succeed in moving through a wide variety of harsh environments. Therefore, it can be desirable to copy their selection of locomotion mechanisms. However, replicating nature in this regard is extremely difficult for several reasons. To begin with, mechanical complexity is easily achieved in biological systems through structural replication. Cell division, in combination with specialization, can readily produce a millipede with several hundred legs and several tens of thousands of individually sensed cilia. In man-made structures, each part must be fabricated individually, and so no such economies of scale exist. Additionally, the cell is a microscopic building block that enables extreme miniaturization. With very small size and weight, insects achieve a level of robustness that we have not been able to match with human fabrication techniques. Finally, the biological energy storage system and the muscular and hydraulic activation systems used by large animals and insects achieve torque, response time, and conversion efficiencies that far exceed similarly scaled man-made systems.

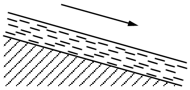
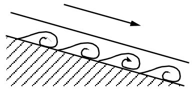
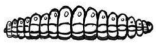
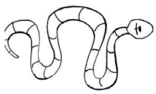
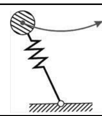
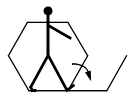
Type of motion	Resistance to motion	Basic kinematics of motion
Flow in a Channel 	Hydrodynamic forces	Eddies 
Crawl 	Friction forces	 Longitudinal vibration
Sliding 	Friction forces	 Transverse vibration
Running 	Loss of kinetic energy	Periodic bouncing on a spring 
Walking 	Loss of kinetic energy	Rolling of a polygon (see figure 2.2) 

Figure 2.1
Locomotion mechanisms used in biological systems.

Owing to these limitations, mobile robots generally locomote either using wheeled mechanisms, a well-known human technology for vehicles, or using a small number of articulated legs, the simplest of the biological approaches to locomotion (see figure 2.2).

In general, legged locomotion requires higher degrees of freedom and therefore greater mechanical complexity than wheeled locomotion. Wheels, in addition to being simple, are extremely well suited to flat ground. As figure 2.3 depicts, on flat surfaces wheeled locomotion is one to two orders of magnitude more efficient than legged locomotion. The railway is ideally engineered for wheeled locomotion because rolling friction is minimized on a hard and flat steel surface. But as the surface becomes soft, wheeled locomotion accumulates inefficiencies due to rolling friction, whereas legged locomotion suffers much less because it consists only of point contacts with the ground. This is demonstrated in figure 2.3 by the dramatic loss of efficiency in the case of a tire on soft ground.

In effect, the efficiency of wheeled locomotion depends greatly on environmental qualities, particularly the flatness and hardness of the ground, while the efficiency of legged

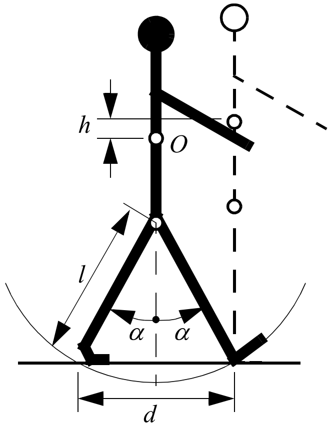


Figure 2.2
A biped walking system can be approximated by a rolling polygon, with sides equal in length *d* to the span of the step. As the step size decreases, the polygon approaches a circle or wheel with the radius *l*.

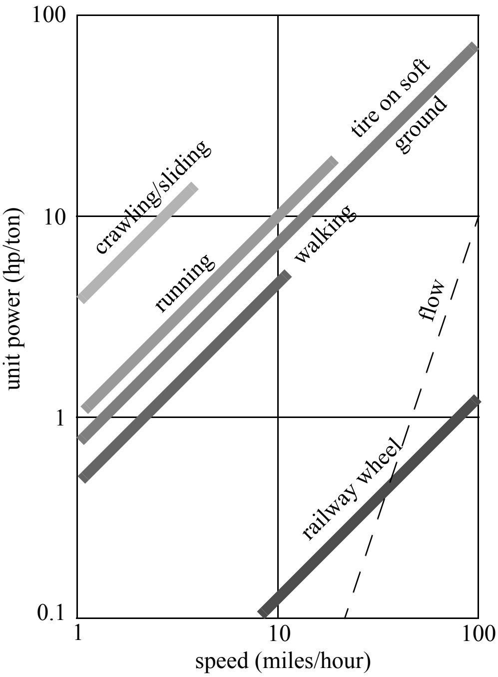


Figure 2.3
Specific power versus attainable speed of various locomotion mechanisms [52].

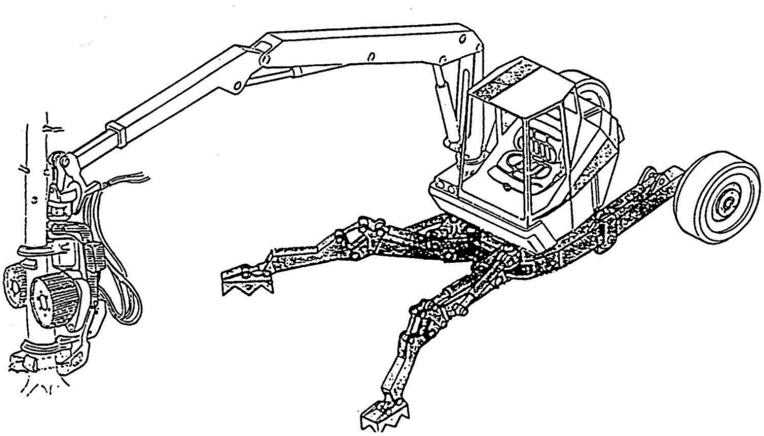


Figure 2.4
RoboTrac, a hybrid wheel-leg vehicle for rough terrain [282].

locomotion depends on the leg mass and body mass, both of which the robot must support at various points in a legged gait.

It is understandable, therefore, that nature favors legged locomotion, since locomotion systems in nature must operate on rough and unstructured terrain. For example, in the case of insects in a forest, the vertical variation in ground height is often an order of magnitude greater than the total height of the insect. By the same token, the human environment frequently consists of engineered, smooth surfaces, both indoors and outdoors. Therefore, it is also understandable that virtually all industrial applications of mobile robotics utilize some form of wheeled locomotion. Recently, for more natural outdoor environments, there has been some progress toward hybrid and legged industrial robots such as the forestry robot shown in figure 2.4.

In section 2.1.1, we present general considerations that concern all forms of mobile robot locomotion. Following this, in sections 2.2. 2.3, and 2.4 we present overviews of legged locomotion, wheeled locomotion, and aerial locomotion techniques for mobile robots.

2.1.1 Key issues for locomotion

Locomotion is the complement of manipulation. In manipulation, the robot arm is fixed but moves objects in the workspace by imparting force to them. In locomotion, the environment is fixed and the robot moves by imparting force to the environment. In both cases, the scientific basis is the study of actuators that generate interaction forces and mechanisms that implement desired kinematic and dynamic properties. Locomotion and manipulation thus share the same core issues of stability, contact characteristics, and environmental type:

- stability
  - number and geometry of contact points
  - center of gravity
  - static/dynamic stability
  - inclination of terrain
- characteristics of contact
  - contact point/path size and shape
  - angle of contact
  - friction
- type of environment
  - structure
  - medium (e.g., water, air, soft or hard ground)

A theoretical analysis of locomotion begins with mechanics and physics. From this starting point, we can formally define and analyze all manner of mobile robot locomotion systems. However, this book focuses on the mobile robot *navigation* problem, particularly stressing perception, localization, and cognition. Thus, we will not delve deeply into the physical basis of locomotion. Nevertheless, the three remaining sections in this chapter present overviews of issues in legged locomotion [52], wheeled locomotion, and aerial locomotion. Chapter 3 presents a more detailed analysis of the kinematics and control of wheeled mobile robots.

2.2 Legged Mobile Robots

Legged locomotion is characterized by a series of point contacts between the robot and the ground. The key advantages include adaptability and maneuverability in rough terrain (figure 2.5). Because only a set of point contacts is required, the quality of the ground between those points does not matter as long as the robot can maintain adequate ground clearance. In addition, a walking robot is capable of crossing a hole or chasm so long as its reach exceeds the width of the hole. A final advantage of legged locomotion is the potential to manipulate objects in the environment with great skill. An excellent insect example, the dung beetle, is capable of rolling a ball while locomoting by way of its dexterous front legs.

The main disadvantages of legged locomotion include power and mechanical complexity. The leg, which may include several degrees of freedom, must be capable of sustaining part of the robot’s total weight, and in many robots it must be capable of lifting and lowering the robot. Additionally, high maneuverability will only be achieved if the legs have a

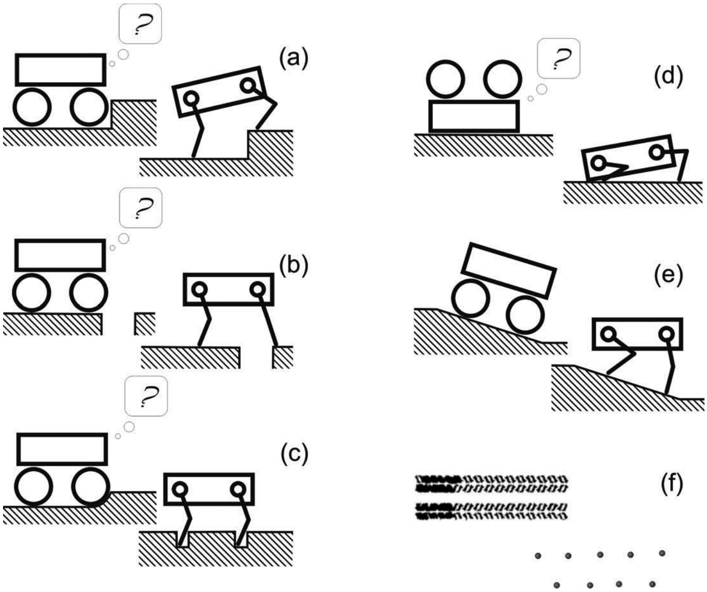


Figure 2.5 Legged robots are particularly suited for rough terrain, where they are able to traverse obstacles such as steps (a), gaps (b), or sandy patches (c) that are impassable for wheeled systems. Additionally, the high number of degrees of freedom allows the robot to stand up when fallen (d) and keep its payload leveled (e). Because legged systems do not require a continuous path for support, they can rely on a few selected footholds, which also reduces the environmental impact (f). Image courtesy of D. Remy.

sufficient number of degrees of freedom to impart forces in a number of different directions.

2.2.1 Leg configurations and stability

Because legged robots are biologically inspired, it is instructive to examine biologically successful legged systems. A number of different leg configurations have been successful in a variety of organisms (figure 2.6). Large animals, such as mammals and reptiles, have four legs, whereas insects have six or more legs. In some mammals, the ability to walk on only two legs has been perfected. Especially in the case of humans, balance has progressed to the point that we can even jump with one leg.[1] This exceptional maneuverability comes at a price: much more complex active control to maintain balance.

1. In child development, one of the tests used to determine if the child is acquiring advanced locomotion skills is the ability to jump on one leg.

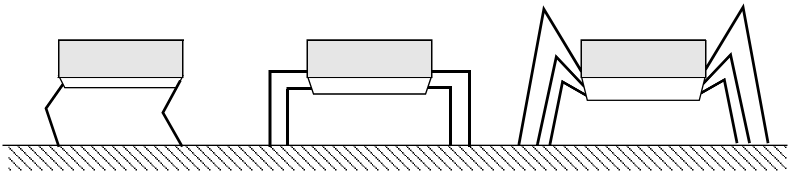


Figure 2.6
Arrangement of the legs of various animals.

In contrast, a creature with three legs can exhibit a static, stable pose provided that it can ensure that its center of gravity is within the tripod of ground contact. Static stability, demonstrated by a three-legged stool, means that balance is maintained with no need for motion. A small deviation from stability (e.g., gently pushing the stool) is passively corrected toward the stable pose when the upsetting force stops.

But a robot must be able to lift its legs in order to walk. In order to achieve static walking, a robot must have at least four legs, moving one of it at a time. For six legs, it is possible to design a gait in which a statically stable tripod of legs is in contact with the ground at all times (figure 2.9).

Insects and spiders are immediately able to walk when born. For them, the problem of balance during walking is relatively simple. Mammals, with four legs, can achieve static walking, which, however, is less stable due to the high center of gravity than, for example, reptile walking. Fawns, for example, spend several minutes attempting to stand before they are able to do so, then spend several more minutes learning to walk without falling. Humans, with two legs, can also stand statically stable due to their large feet. Infants require months to stand and walk, and even longer to learn to jump, run, and stand on one leg.

There is also the potential for great variety in the complexity of each individual leg. Once again, the biological world provides ample examples at both extremes. For instance, in the case of the caterpillar, each leg is extended using hydraulic pressure by constricting the body cavity and forcing an increase in pressure, and each leg is retracted longitudinally by relaxing the hydraulic pressure, then activating a single tensile muscle that pulls the leg in toward the body. Each leg has only a single degree of freedom, which is oriented longitudinally along the leg. Forward locomotion depends on the hydraulic pressure in the body, which extends the distance between pairs of legs. The caterpillar leg is therefore mechanically very simple, using a minimal number of extrinsic muscles to achieve complex overall locomotion.

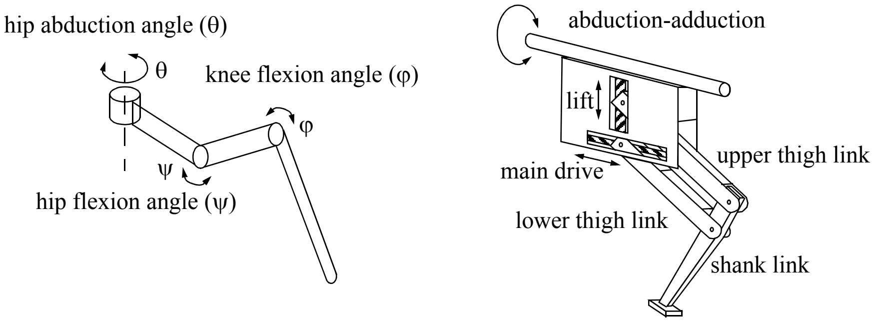


Figure 2.7
Two examples of legs with three degrees of freedom.

At the other extreme, the human leg has more than seven major degrees of freedom, combined with further actuation at the toes. More than fifteen muscle groups actuate eight complex joints.

In the case of legged mobile robots, a minimum of two degrees of freedom is generally required to move a leg forward by lifting the leg and swinging it forward. More common is the addition of a third degree of freedom for more complex maneuvers, resulting in legs such as those shown in figure 2.7. Recent successes in the creation of bipedal walking robots have added a fourth degree of freedom at the ankle joint. The ankle enables the robot to shift the resulting force vector of the ground contact by actuating the pose of the sole of the foot.

In general, adding degrees of freedom to a robot leg increases the maneuverability of the robot, both augmenting the range of terrains on which it can travel and the ability of the robot to travel with a variety of gaits. The primary disadvantages of additional joints and actuators are, of course, energy, control, and mass. Additional actuators require energy and control, and they also add to leg mass, further increasing power and load requirements on existing actuators.

In the case of a multilegged mobile robot, there is the issue of leg coordination for locomotion, or gait control. The number of possible gaits depends on the number of legs [52]. The gait is a sequence of lift and release events for the individual legs. For a mobile robot with k legs, the total number of distinct event sequences N for a walking machine is:

$$N = (2k-1)! \tag{2.1}$$

For a biped walker $k = 2$ legs, the number of distinct event sequences N is:

$$N = (2k-1)! = 3! = 3 \cdot 2 \cdot 1 = 6 \tag{2.2}$$

The six distinct event sequences that can be combined for more complex sequences are:

1. both legs down – right down / left up – both legs down;
2. both legs down – right leg up / left leg down – both legs down;
3. both legs down – both legs up – both legs down;
4. right leg down / left leg up – right leg up / left leg down – right leg down / left leg up;
5. right leg down / left leg up – both legs up – right leg down / left leg up;
6. right leg up / left leg down – both legs up – right leg up / left leg down.

Of course, this quickly grows quite large. For example, a robot with six legs has far more events:

$$N = 11! = 39916800, \tag{2.3}$$

with an even higher number of theoretically possible gaits.

Figures 2.8 and 2.9 depict several four-legged gaits and the static six-legged tripod gait.

2.2.2 Consideration of dynamics

The *cost of transportation* expresses how much energy a robot uses to travel a certain distance. To better compare differently sized systems, this value is usually normalized by the robot's weight and expressed in $J/(N \cdot m)$—a dimensionless quantity—where J stands for joule, N for newton, and m for meter. When a robot moves with constant speed on a level surface, its potential and kinetic energy remain constant. In theory, no physical work is necessary to keep it moving, which makes it possible to get from one place to another with zero cost of transportation. In reality, however, some energy is always dissipated, and robots have to be equipped with actuators and batteries to compensate for the losses. For a wheeled robot, the main causes for such losses are the friction in the drive train and the rolling resistance of the wheels on the ground. Similarly, friction is present in the joints of legged systems and energy is dissipated by the foot-ground interaction. However, these effects cannot explain why legged systems usually consume considerably more energy than their wheeled counterparts. The bulk part of energy loss actually originates in the fact that legs—in contrast to wheels or tracks—are not performing a continuous motion, but are periodically moving back and forth. Joints have to undergo alternating phases of acceleration and deceleration, and, as we have only a very limited ability to recuperate the negative work of deceleration, energy is irrecoverably lost in the process. Because of the segmented structure of

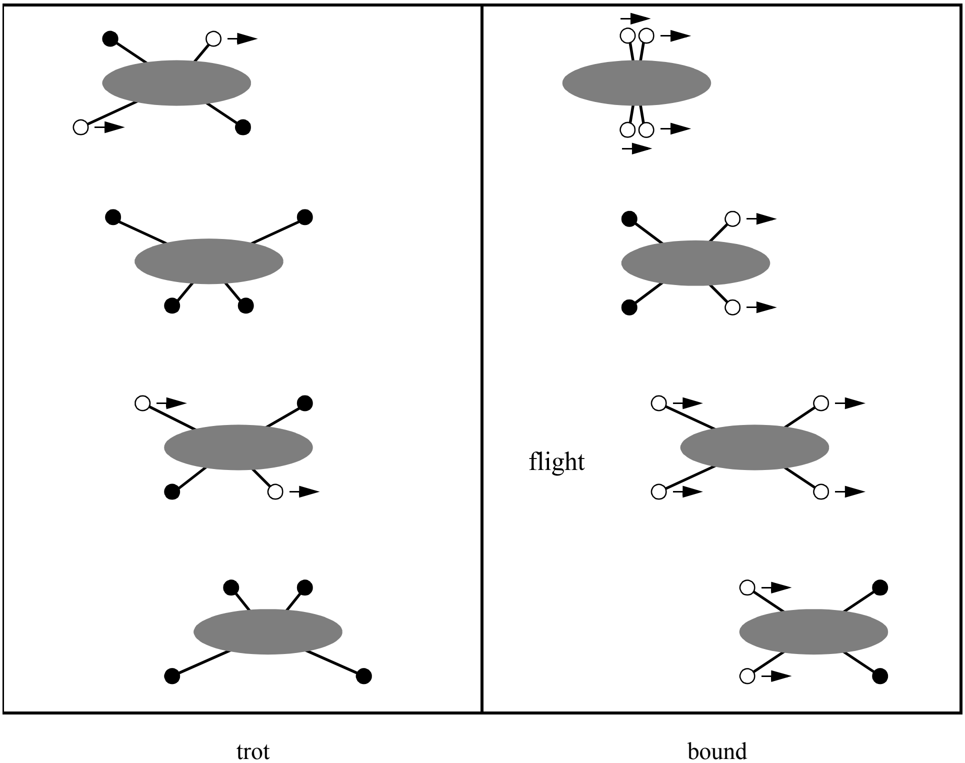


Figure 2.8
Two gaits with four legs.

the legs, it can even happen that energy that is fed into one joint (e.g., the knee) is simultaneously dissipated in another joint (e.g., the hip) without creating any net work at the feet. Therefore, actuators are working against each other [180].

A solution to this problem is a better exploitation of the dynamics of the mechanical structure. The natural oscillations of pendula and springs, can—if they are well designed—automatically create the required periodic motions. For example, the motion of a swinging leg can be grasped by the dynamics of a simple double pendulum. If the lengths and the inertial properties of the leg segments are correctly selected, such a pendulum will automatically swing forward, clear the ground, and extend the leg to touch the ground in front of the main body. If, on the other side, a foot is on the ground and the leg is kept stiff, an inverted pendulum motion will efficiently propel the main body forward. During running, these inverted pendulum dynamics are additionally enhanced by springs, which store

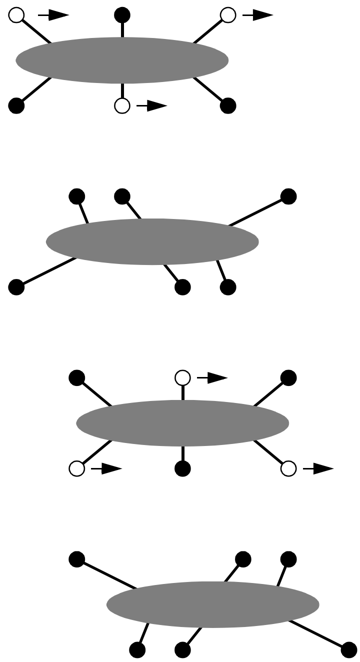


Figure 2.9
Static walking with six legs. A tripod formed by three legs always exists.

energy during the ground phase and allow the main body to take off for the subsequent flight phase (figure 2.10).

With this approach it is, in fact, possible to build legged robots that do not have actuation of any kind. Such passive dynamic walkers [211,344] walk down a shallow incline (which compensates for frictional losses), but, because no actuators are present, no negative work is performed and energetic losses due to braking are eliminated. In addition to creating a periodic motion, the dynamics of such walkers must be designed to ensure dynamic stability. The mechanical structure must passively reject small disturbances which would otherwise accumulate over time and eventually cause the robot to fall. Actuated robots built according to these principles can walk with a remarkable efficiency [104] and one of them, the Cornell Ranger, currently holds the distance record for autonomous legged robots [345] (figure 2.11).

Passive dynamic walkers also have a striking similarity to the physique and motion patters of human gait. During the evolution, humans and animals have become quite efficient walkers, and a look at electromyography recordings shows that during walking our muscles

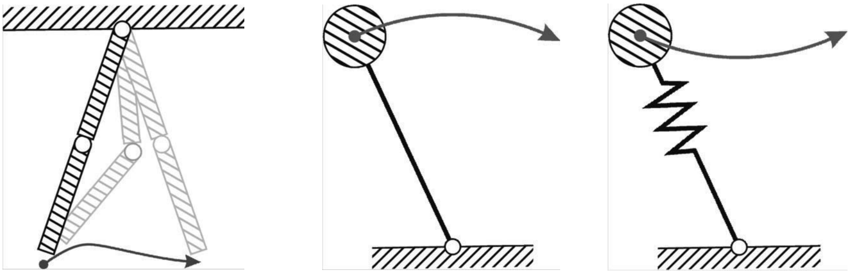


Figure 2.10 Dynamic elements that are exploited in energy efficient walking include the double-pendulum for leg swing, the inverted pendulum for the stance phase of walking, and springy legs for running gaits. Image courtesy of D. Remy.

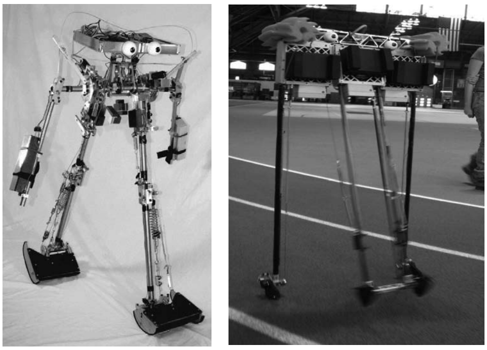


Figure 2.11 The Cornell powered two-legged and four-legged biped robots. In April 2008, the four-legged bipedal robot Ranger walked a distance of 9.07 km without being touched by a person. Image courtesy of the Biorobotics and Locomotion Lab—Cornell University.

are far less active than one would expect for a task in which most of our limbs are in constant motion. To some degree, humans are passive dynamic walkers.

It is obvious that such an exploitation of the mechanical dynamics can only work at specific velocities. When the locomotion speed changes, characteristic properties such as stride length or stride frequency change as well, and—because these have to be matched with the spring and pendulum oscillations of the mechanical structure—more and more actuator effort is needed to force the joints to follow their required trajectories. For human walking, the optimal walking speed is approximately 1 m/s, which is also the range that subjectively feels most comfortable. For both higher and lower speeds, the cost of transportation will increase, and more energy is needed to travel the same distance. For this reason, humans change their gait from walking to running when they want to travel at higher speeds, which is more efficient than just performing the same motion faster and faster.

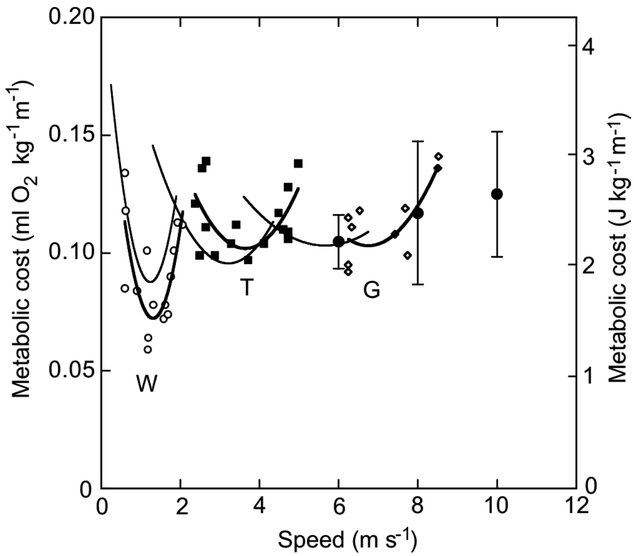


Figure 2.12 Metabolic cost of transportation (here normalized by body mass) for different gaits of horses: walking (W), running (R), and galloping (G). Each gait has a specific velocity that minimizes energy expenditure. This explains why animals and humans change their gait when traveling at different speeds. Image courtesy of A. E. Minetti [221].

Changing the gait allows us to use a different set of natural dynamics, which better matches the stride frequency and step length that are needed for higher velocities. Likewise, the wide variety of gaits found in animals can be explained by the use of different sets of dynamic elements, which minimize the energy necessary for transportation (figure 2.12).

2.2.3 Examples of legged robot locomotion

Although there are no high-volume industrial applications to date, legged locomotion is an important area of long-term research. Several interesting designs are presented here, beginning with the one-legged robot and finishing with six-legged robots.

2.2.3.1 One leg

The minimum number of legs a legged robot can have is, of course, one. Minimizing the number of legs is beneficial for several reasons. Body mass is particularly important to walking machines, and the single leg minimizes cumulative leg mass. Leg coordination is required when a robot has several legs, but with one leg no such coordination is needed. Perhaps most important, the one-legged robot maximizes the basic advantage of legged locomotion: legs have single points of contact with the ground in lieu of an entire track, as

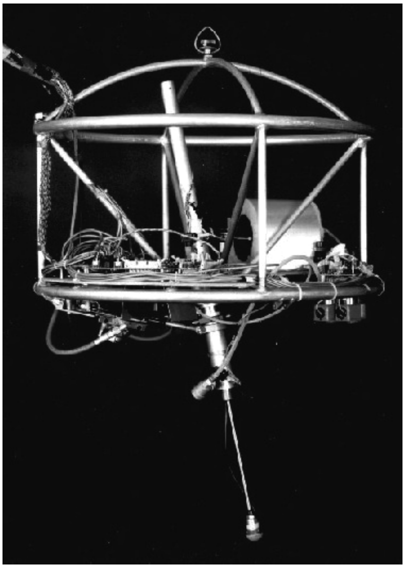
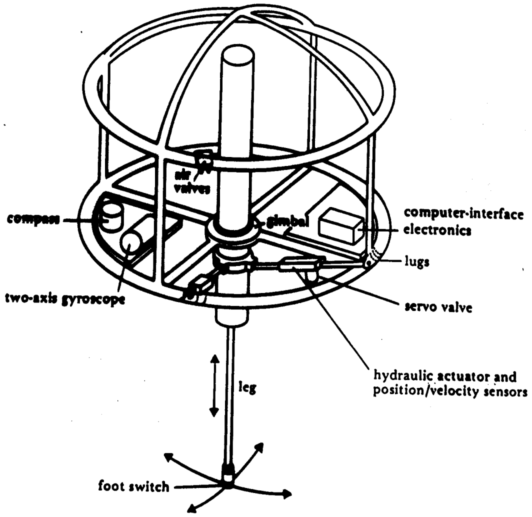



Figure 2.13
The Raibert hopper [42, 264]. Image courtesy of the LegLab and Marc Raibert. © 1983.

with wheels. A single-legged robot requires only a sequence of single contacts, making it amenable to the roughest terrain. Furthermore, a hopping robot can dynamically cross a gap that is larger than its stride by taking a running start, whereas a multilegged walking robot that cannot run is limited to crossing gaps that are as large as its reach.

The major challenge in creating a single-legged robot is balance. For a robot with one leg, static walking is not only impossible, but static stability when stationary is also impossible. The robot must actively balance itself by either changing its center of gravity or by imparting corrective forces. Thus, the successful single-legged robot must be dynamically stable.

Figure 2.13 shows the Raibert hopper [42, 264], one of the best-known single-legged hopping robots created. This robot makes continuous corrections to body attitude and to robot velocity by adjusting the leg angle with respect to the body. The actuation is hydraulic, including high-power longitudinal extension of the leg during stance to hop back into the air. Although powerful, these actuators require a large, off-board hydraulic pump to be connected to the robot at all times.

Figure 2.14 shows a more energy-efficient design that takes advantage of well-designed mechanical dynamics [83]. Instead of supplying power by means of an off-board hydraulic pump, the bow leg hopper is designed to capture the kinetic energy of the robot as it lands,

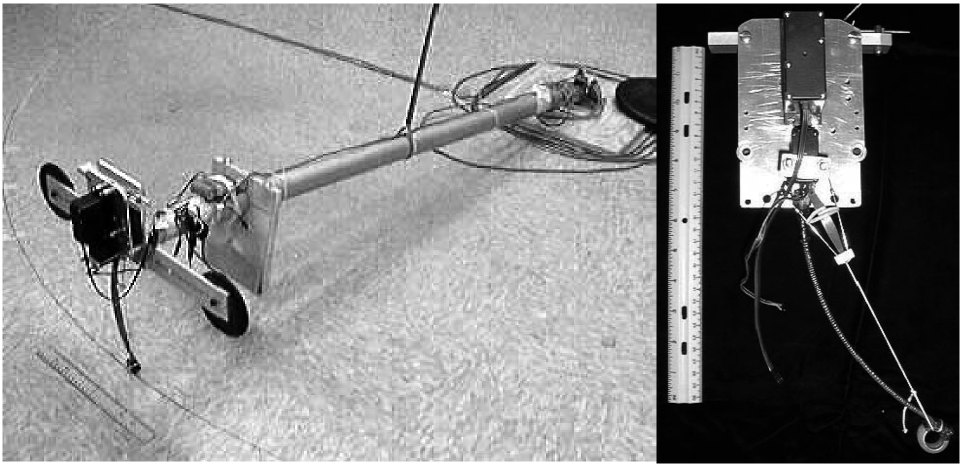


Figure 2.14
The 2D single bow leg hopper [83]. Image courtesy of H. Benjamin Brown and Garth Zeglin, CMU.

using an efficient bow spring leg. This spring returns approximately 85% of the energy, meaning that stable hopping requires only the addition of 15% of the required energy on each hop. This robot, which is constrained along one axis by a boom, has demonstrated continuous hopping for 20 minutes using a single set of batteries carried on board the robot. As with the Raibert hopper, the bow leg hopper controls velocity by changing the angle of the leg to the body at the hip joint.

Ringrose [266] demonstrates the very important duality of mechanics and controls as applied to a single-legged hopping machine. Often clever mechanical design can perform the same operations as complex active control circuitry. In this robot, the physical shape of the foot is exactly the right curve so that when the robot lands without being perfectly vertical, the proper corrective force is provided from the impact, making the robot vertical by the next landing. This robot is dynamically stable, and is furthermore passive. The correction is provided by physical interactions between the robot and its environment, with no computer or any active control in the loop.

2.2.3.2 Two legs (biped)

A variety of successful bipedal robots have been demonstrated over the past ten years. Two legged robots have been shown to run, jump, travel up and down stairways, and even do aerial tricks such as somersaults. In the commercial sector, both Honda and Sony have made significant advances over the past decade that have enabled highly capable bipedal robots. Both companies designed small, powered joints that achieve power-to-weight per-

Specifications:

Weight:	7 kg
Height:	58 cm
Neck DOF:	4
Body DOF:	2
Arm DOF:	2×5
Legs DOF:	2×6
Five-finger Hands	

Figure 2.15
The Sony SDR-4X II. © 2003 Sony Corporation.

formance unheard of in commercially available servomotors. These new "intelligent" servos provide not only strong actuation but also compliant actuation by means of torque sensing and closed-loop control.

The Sony Dream Robot, model SDR-4X II, is shown in figure 2.15. This current model is the result of research begun in 1997 with the basic objective of motion entertainment and communication entertainment (i.e., dancing and singing). This robot with thirty-eight degrees of freedom has seven microphones for fine localization of sound, image person recognition, on-board miniature stereo depth-map reconstruction, and limited speech recognition. Given the goal of fluid and entertaining motion, Sony spent considerable effort designing a motion prototyping application system to enable their engineers to script dances in a straightforward manner. Note that the SDR-4X II is relatively small, standing at 58 cm and weighing only 7 kg.

The Honda humanoid project has a significant history, but, again, it has tackled the very important engineering challenge of actuation. Figure 2.16 shows model *P2*, which is an immediate predecessor to the most recent Asimo (advanced step in innovative mobility) model. Note that the latest Honda Asimo model is still much larger than the SDR-4X at 120 cm tall and 52 kg. This enables practical mobility in the human world of stairs and ledges while maintaining a nonthreatening size and posture. Perhaps the first robot to demonstrate

Specifications:

Maximum speed:	2 km/h
Autonomy:	15 min
Weight:	210 kg
Height:	1.82 m
Leg DOF:	2×6
Arm DOF:	2×7

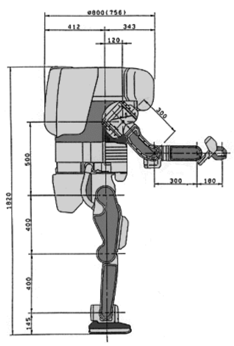
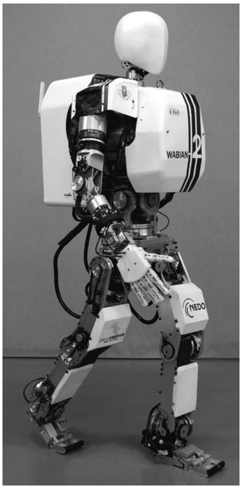


Figure 2.16
The humanoid robot P2 from Honda, Japan. © Honda Motor Cooperation.

biomimetic bipedal stair climbing and descending, these Honda humanoid series robots are being designed not for entertainment purposes but as human aids throughout society. Honda refers, for instance, to the height of Asimo as the minimum height that enables it to manage nonetheless operation of the human world, for instance, control of light switches.

An important feature of bipedal robots is their anthropomorphic shape. They can be built to have the same approximate dimensions as humans, and this makes them excellent vehicles for research in human-robot interaction. WABIAN-2R is a robot built at Waseda University, Japan (figure 2.17) for just such research [255]. WABIAN-2R is designed to emulate human motion, and it is even designed to dance like a human.

Bipedal robots can only be statically stable within some limits, and so robots such as P2 and WABIAN-2R generally must perform continuous balance-correcting servoing even when standing still. Furthermore, each leg must have sufficient capacity to support the full weight of the robot. In the case of four-legged robots, the balance problem is facilitated along with the load requirements of each leg. An elegant design of a biped robot is the Spring Flamingo of MIT (figure 2.18). This robot inserts springs in series with the leg actuators to achieve a more elastic gait. Combined with “kneecaps” that limit knee joint angles, the Flamingo achieves surprisingly biomimetic motion.



Specifications:

Weight:	64 [kg] (with batteries)
Height:	1.55 [m]

DOF:

Leg:	6×2
Foot:	1×2 (passive)
Waist:	2
Trunk:	2
Arm:	7×2
Hand:	3×2
Neck:	3

Figure 2.17
The humanoid robot WABIAN-2R developed at Waseda University in Japan [255] (http://www.takanishi.mech.waseda.ac.jp/). © Atsuo Takanishi Lab, Waseda University.

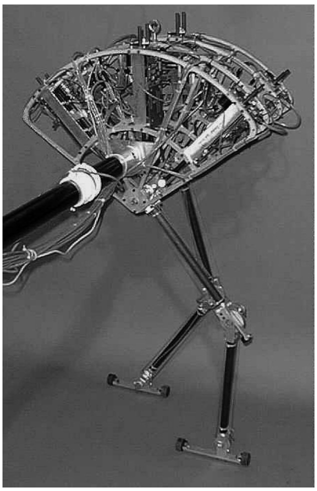
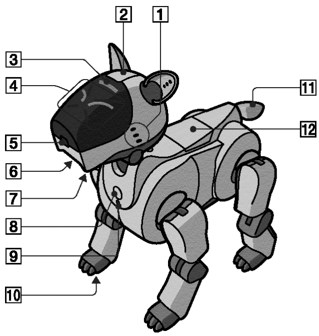


Figure 2.18
The Spring Flamingo developed at MIT [262]. Image courtesy of Jerry Pratt, MIT Leg Laboratory.



ERS-110 © 1999 Sony Corporation

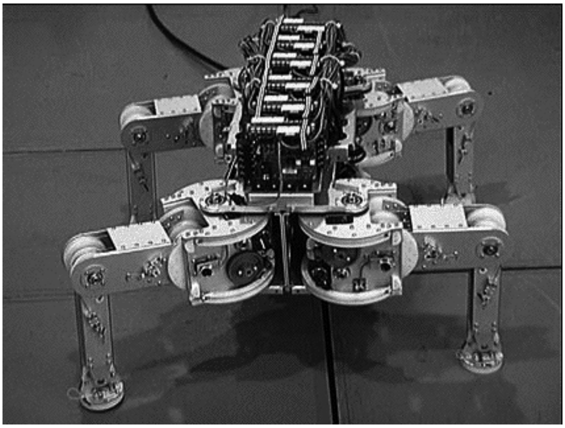
ERS-210 © 2000 Sony Corporation

1 Stereo microphone: Allows AIBO to pick up surrounding sounds.
2 Head sensor: Senses when a person taps or pets AIBO on the head.
3 Mode indicator: Shows AIBO's operation mode.
4 Eye lights: These light up in blue-green or red to indicate AIBO's emotional state.
5 Color camera: Allows AIBO to search for objects and recognize them by color and movement.
6 Speaker: Emits various musical tones and sound effects.
7 Chin sensor: Senses when a person touches AIBO on the chin.
8 Pause button: Press to activate AIBO or to pause AIBO.
9 Chest light: Gives information about the status of the robot.
10 Paw sensors: Located on the bottom of each paw.
11 Tail light: Lights up blue or orange to show AIBO's emotional state.
12 Back sensor: Senses when a person touches AIBO on the back.

Figure 2.19
AIBO, the artificial dog from Sony, Japan.

2.2.3.3 Four legs (quadruped)

Although standing still on four legs is passively stable, walking remains challenging because to remain stable, the robot's center of gravity must be actively shifted during the gait. Sony invested several million dollars to develop a four-legged robot called AIBO (figure 2.19). To create this robot, Sony produced both a new robot operating system that is near real-time and new geared servomotors that are of sufficiently high torque to support the robot, yet are back-drivable for safety. In addition to developing custom motors and software, Sony incorporated a color vision system that enables AIBO to chase a brightly colored ball. The robot is able to function for at most one hour before requiring recharging. Early sales of the robot have been very strong, with more than 60,000 units sold in the first year. Nevertheless, the number of motors and the technology investment behind this robot dog resulted in a very high price of approximately $1,500.



Specifications:

Weight:	19 kg
Height:	0.25 m
DOF:	4×3

Figure 2.20
Titan VIII, a quadruped robot developed at Tokyo Institute of Technology (http://www-robot.mes.titech.ac.jp). © Tokyo Institute of Technology.

Four-legged robots have the potential to serve as effective artifacts for research in human-robot interaction (figure 2.20). Humans can treat the Sony robot, for example, as a pet and might develop an emotional relationship similar to that between man and dog. Furthermore, Sony has designed AIBO's walking style and general behavior to emulate learning and maturation, resulting in dynamic behavior over time that is more interesting for the owner who can track the changing behavior. As the challenges of high energy storage and motor technology are solved, it is likely that quadruped robots much more capable than AIBO will become common throughout the human environment.

BigDog and LittleDog (figure 2.21) are two recent examples of quadruped robots developed by Boston Dynamics and commissioned by the American Defense Advanced Research Projects Agency (DARPA). BigDog is a rough-terrain robot that walks, runs, climbs, and carries heavy loads. It is powered by an engine that drives a hydraulic actuation system. Its legs are articulated like an animal's, with compliant elements to absorb shock and recycle energy between two steps. The goal of this project is to make it able go anywhere people and animals can go. The program is funded by the Tactical Technology Office at DARPA. Conversely, LittleDog is a small-size robot designed for research on learning locomotion. Each leg has a large range of motion and is powered by three electric motors. Therefore, the robot is strong enough for climbing and dynamic locomotion gaits.

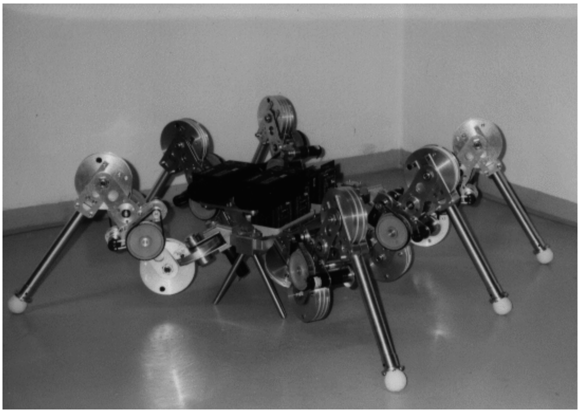
Another example four-legged robot is ALoF, the quadruped developed at the ASL (ETH Zurich) (figure 2.22).This robot serves as a platform to study energy-efficient locomotion. This is done by exploiting passive dynamic in ways that have shown to be effective in bipedal robots, as has been explained in section 2.2.2.

Figure 2.21 LittleDog and BigDog quadruped robots developed by Boston Dynamics. Image courtesy of Boston Dynamics (http://www.bostondynamics.com).

Figure 2.22 ALoF, the quadruped robot developed at the ASL (ETH Zurich), has been built to investigate energy efficient locomotion. This is done by exploiting passive dynamics (http://www.asl.ethz.ch/). © ASL-ETH Zurich.

2.2.3.4 Six legs (hexapod)

Six-legged configurations have been extremely popular in mobile robotics because of their static stability during walking, thus reducing the control complexity (figures 2.23 and 1.3). In most cases, each leg has three degrees of freedom, including hip flexion, knee flexion,



Specifications:

Maximum speed:	0.5 m/s
Weight:	16 kg
Height:	0.3 m
Length:	0.7 m
No. of legs:	6
DOF in total:	6×3
Power consumption:	10 W

Figure 2.23
Lauron II, a hexapod platform developed at the University of Karlsruhe, Germany.
© University of Karlsruhe.

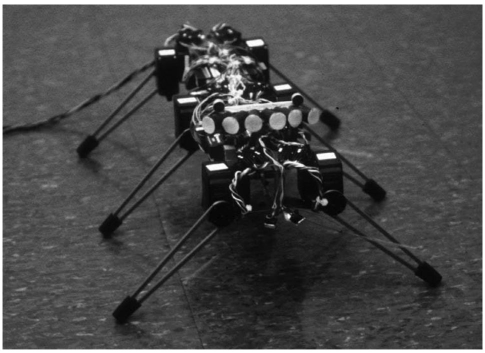


Figure 2.24
Genghis, one of the most famous walking robots from MIT, uses hobby servomotors as its actuators (http://www.ai.mit.edu/projects/genghis). © MIT AI Lab.

and hip abduction (see figure 2.7). Genghis is a commercially available hobby robot that has six legs, each of which has two degrees of freedom provided by hobby servos (figure 2.24). Such a robot, which consists only of hip flexion and hip abduction, has less maneuverability in rough terrain but performs quite well on flat ground. Because it consists of a straightforward arrangement of servomotors and straight legs, such robots can be readily built by a robot hobbyist.

Insects, which are arguably the most successful locomoting creatures on earth, excel at traversing all forms of terrain with six legs, even upside down. Currently, the gap between the capabilities of six-legged insects and artificial six-legged robots is still quite large. Interestingly, this is not due to a lack of sufficient numbers of degrees of freedom on the robots. Rather, insects combine a small number of active degrees of freedom with passive structures, such as microscopic barbs and textured pads, that increase the gripping strength of each leg significantly. Robotic research into such passive tip structures has only recently begun. For example, a research group is attempting to re-create the complete mechanical function of the cockroach leg [124].

It is clear from these examples that legged robots have much progress to make before they are competitive with their biological equivalents. Nevertheless, significant gains have been realized recently, primarily due to advances in motor design. Creating actuation systems that approach the efficiency of animal muscles remains far from the reach of robotics, as does energy storage with the energy densities found in organic life forms.

2.3 Wheeled Mobile Robots

The wheel has been by far the most popular locomotion mechanism in mobile robotics and in man-made vehicles in general. It can achieve very good efficiencies, as demonstrated in figure 2.3, and it does so with a relatively simple mechanical implementation.

In addition, balance is not usually a research problem in wheeled robot designs, because wheeled robots are almost always designed so that all wheels are in ground contact at all times. Thus, three wheels are sufficient to guarantee stable balance, although, as we shall see below, two-wheeled robots can also be stable. When more than three wheels are used, a suspension system is required to allow all wheels to maintain ground contact when the robot encounters uneven terrain.

Instead of worrying about balance, wheeled robot research tends to focus on the problems of traction and stability, maneuverability, and control: can the robot wheels provide sufficient traction and stability for the robot to cover all of the desired terrain, and does the robot's wheeled configuration enable sufficient control over the velocity of the robot?

2.3.1 Wheeled locomotion: The design space

As we shall see, there is a very large space of possible wheel configurations when one considers possible techniques for mobile robot locomotion. We begin by discussing the wheel in detail, since there are a number of different wheel types with specific strengths and weaknesses. We then examine complete wheel configurations that deliver particular forms of locomotion for a mobile robot.

2.3.1.1 Wheel design

There are four major wheel classes, as shown in figure 2.25. They differ widely in their kinematics, and therefore the choice of wheel type has a large effect on the overall kinemat-

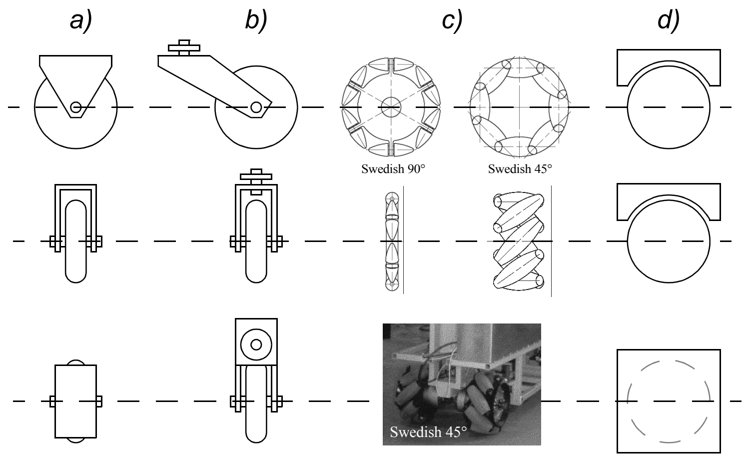


Figure 2.25
The four basic wheel types. (a) Standard wheel: two degrees of freedom; rotation around the (motorized) wheel axle and the contact point.(b) castor wheel: two degrees of freedom; rotation around an offset steering joint. (c) Swedish wheel: three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers, and around the contact point. (d) Ball or spherical wheel: realization technically difficult.

ics of the mobile robot. The standard wheel and the castor wheel have a primary axis of rotation and are thus highly directional. To move in a different direction, the wheel must be steered first along a vertical axis. The key difference between these two wheels is that the standard wheel can accomplish this steering motion with no side effects, since the center of rotation passes through the contact patch with the ground, whereas the castor wheel rotates around an offset axis, causing a force to be imparted to the robot chassis during steering.

The Swedish wheel and the spherical wheel are both designs that are less constrained by directionality than the conventional standard wheel. The Swedish wheel functions as a normal wheel but provides low resistance in another direction as well, sometimes perpendicular to the conventional direction, as in the Swedish 90, and sometimes at an intermediate angle, as in the Swedish 45. The small rollers attached around the circumference of the wheel are passive and the wheel's primary axis serves as the only actively powered joint. The key advantage of this design is that, although the wheel rotation is powered only along the one principal axis (through the axle), the wheel can kinematically move with very little friction along many possible trajectories, not just forward and backward.

The spherical wheel is a truly omnidirectional wheel, often designed so that it may be actively powered to spin along any direction. One mechanism for implementing this spherical design imitates the computer mouse, providing actively powered rollers that rest against the top surface of the sphere and impart rotational force.

Figure 2.26
The Tartan Racing self-driving vehicle developed at CMU, which won the 2007 DARPA Urban Challenge. Image courtesy of the Tartan Racing Team—http://www.tartanracing.org.

Regardless of what wheel is used, in robots designed for all-terrain environments and in robots with more than three wheels, a suspension system is normally required to maintain wheel contact with the ground. One of the simplest approaches to suspension is to design flexibility into the wheel itself. For instance, in the case of some four-wheeled indoor robots that use castor wheels, manufacturers have applied a deformable tire of soft rubber to the wheel to create a primitive suspension. Of course, this limited solution cannot compete with a sophisticated suspension system in applications where the robot needs a more dynamic suspension for significantly nonflat terrain.

2.3.1.2 Wheel geometry

The choice of wheel types for a mobile robot is strongly linked to the choice of wheel arrangement, or wheel geometry. The mobile robot designer must consider these two issues simultaneously when designing the locomoting mechanism of a wheeled robot. Why do wheel type and wheel geometry matter? Three fundamental characteristics of a robot are governed by these choices: maneuverability, controllability, and stability.

Unlike automobiles, which are largely designed for a highly standardized environment (the road network), mobile robots are designed for applications in a wide variety of situations. Automobiles all share similar wheel configurations because there is one region in the design space that maximizes maneuverability, controllability, and stability for their standard environment: the paved roadway. However, there is no single wheel configuration that maximizes these qualities for the variety of environments faced by different mobile robots. So you will see great variety in the wheel configurations of mobile robots. In fact, few robots use the Ackerman wheel configuration of the automobile because of its poor maneuverability, with the exception of mobile robots designed for the road system (figure 2.26).

Table 2.1 gives an overview of wheel configurations ordered by the number of wheels. This table shows both the selection of particular wheel types and their geometric configuration on the robot chassis. Note that some of the configurations shown are of little use in mobile robot applications. For instance, the two-wheeled bicycle arrangement has moderate maneuverability and poor controllability. Like a single-legged hopping machine, it can never stand still. Nevertheless, this table provides an indication of the large variety of wheel configurations that are possible in mobile robot design.

The number of variations in table 2.1 is quite large. However, there are important trends and groupings that can aid in comprehending the advantages and disadvantages of each configuration. We next identify some of the key trade-offs in terms of the three issues we identified earlier: stability, maneuverability, and controllability.

2.3.1.3 Stability

Surprisingly, the minimum number of wheels required for static stability is two. As shown above, a two-wheel differential-drive robot can achieve static stability if the center of mass is below the wheel axle. Cye is a commercial mobile robot that uses this wheel configuration (figure 2.27).

However, under ordinary circumstances such a solution requires wheel diameters that are impractically large. Dynamics can also cause a two-wheeled robot to strike the floor with a third point of contact, for instance, with sufficiently high motor torques from standstill. Conventionally, static stability requires a minimum of three wheels, with the additional caveat that the center of gravity must be contained within the triangle formed by the ground contact points of the wheels. Stability can be further improved by adding more wheels, although once the number of contact points exceeds three, the hyperstatic nature of the geometry will require some form of flexible suspension on uneven terrain.

2.3.1.4 Maneuverability

Some robots are omnidirectional, meaning that they can move at any time in any direction along the ground plane (x, y) regardless of the orientation of the robot around its vertical axis. This level of maneuverability requires wheels that can move in more than just one direction, and so omnidirectional robots usually employ Swedish or spherical wheels that are powered. A good example is Uranus (figure 2.30), a robot that uses four Swedish wheels to rotate and translate independently and without constraints.

In general, the ground clearance of robots with Swedish and spherical wheels is somewhat limited due to the mechanical constraints of constructing omnidirectional wheels. An interesting recent solution to the problem of omnidirectional navigation while solving this ground-clearance problem is the four-castor wheel configuration in which each castor wheel is actively steered and actively translated. In this configuration, the robot is truly omnidirectional because, even if the castor wheels are facing a direction perpendicular to

Table 2.1
Wheel configurations for rolling vehicles

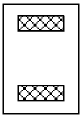
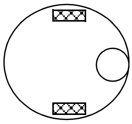
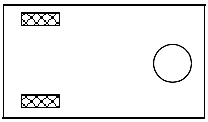
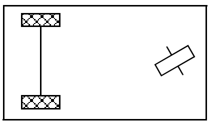
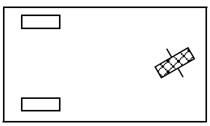
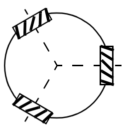
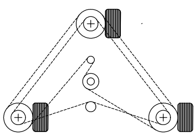
# of wheels	Arrangement	Description	Typical examples
2		One steering wheel in the front, one traction wheel in the rear	Bicycle, motorcycle
		Two-wheel differential drive with the center of mass (COM) below the axle	Cye personal robot
3		Two-wheel centered differential drive with a third point of contact	Nomad Scout, smartRob EPFL
		Two independently driven wheels in the rear/front, one unpowered omnidirectional wheel in the front/rear	Many indoor robots, including the EPFL robots Pygmalion and Alice
		Two connected traction wheels (differential) in rear, one steered free wheel in front	Piaggio minitrucks
		Two free wheels in rear, one steered traction wheel in front	Neptune (Carnegie Mellon University), Hero-1
		Three motorized Swedish or spherical wheels arranged in a triangle; omnidirectional movement is possible	Stanford wheel Tribolo EPFL, Palm Pilot Robot Kit (CMU)
		Three synchronously motorized and steered wheels; the orientation is not controllable	"Synchro drive" Denning MRV-2, Georgia Institute of Technology, I-Robot B24, Nomad 200

Table 2.1
Wheel configurations for rolling vehicles

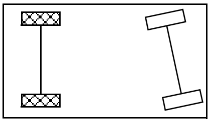
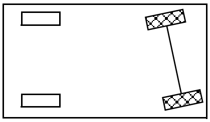
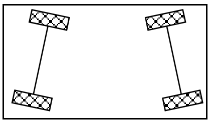
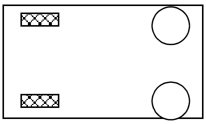
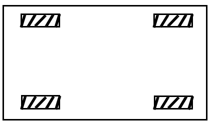
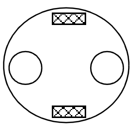
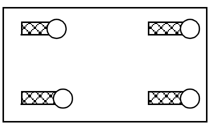
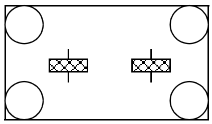
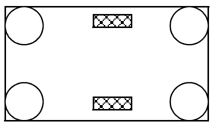
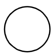
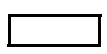
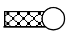
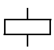
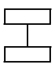
# of wheels	Arrangement	Description	Typical examples
4		Two motorized wheels in the rear, two steered wheels in the front; steering has to be different for the two wheels to avoid slipping/skidding.	Car with rear-wheel drive
		Two motorized and steered wheels in the front, two free wheels in the rear; steering has to be different for the two wheels to avoid slipping/skidding.	Car with front-wheel drive
		Four steered and motorized wheels	Four-wheel drive, four-wheel steering Hyperion (CMU)
		Two traction wheels (differential) in rear/front, two omnidirectional wheels in the front/rear	Charlie (DMT-EPFL)
		Four omnidirectional wheels	Carnegie Mellon Uranus
		Two-wheel differential drive with two additional points of contact	EPFL Khepera, Hyperbot Chip
		Four motorized and steered castor wheels	Nomad XR4000

Table 2.1
Wheel configurations for rolling vehicles

# of wheels	Arrangement	Description	Typical examples
6		Two motorized and steered wheels aligned in center, one omnidirectional wheel at each corner	First
		Two traction wheels (differential) in center, one omnidirectional wheel at each corner	Terregator (Carnegie Mellon University)
Icons for the each wheel type are as follows:			
	unpowered omnidirectional wheel (spherical, castor, Swedish)		
	motorized Swedish wheel (Stanford wheel)		
	unpowered standard wheel		
	motorized standard wheel		
	motorized and steered castor wheel		
	steered standard wheel		
	connected wheels		

the desired direction of travel, the robot can still move in the desired direction by steering these wheels. Because the vertical axis is offset from the ground-contact path, the result of this steering motion is robot motion.

In the research community, other classes of mobile robots are popular that achieve high maneuverability, only slightly inferior to that of the omnidirectional configurations. In such robots, motion in a particular direction may initially require a rotational motion. With a circular chassis and an axis of rotation at the center of the robot, such a robot can spin without

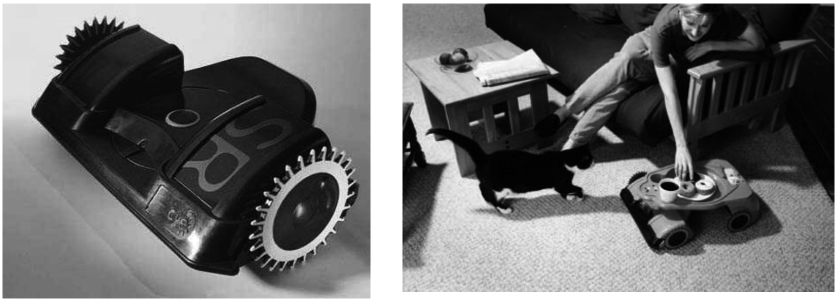


Figure 2.27
Cye, a domestic robot, was designed to vacuum floors and make domestic deliveries.

changing its ground footprint. The most popular such robot is the two-wheel differential-drive robot where the two wheels rotate around the center point of the robot. One or two additional ground contact points may be used for stability, based on the application specifics.

In contrast to these configurations, consider the Ackerman steering configuration common in automobiles. Such a vehicle typically has a turning diameter that is larger than the car. Furthermore, for such a vehicle to move sideways requires a parking maneuver consisting of repeated changes in direction forward and backward. Nevertheless, Ackerman steering geometries have been especially popular in the hobby robotics market, where a robot can be built by starting with a remote control racecar kit and adding sensing and autonomy to the existing mechanism. In addition, the limited maneuverability of Ackerman steering has an important advantage: its directionality and steering geometry provide it with very good lateral stability in high-speed turns.

2.3.1.5 Controllability

There is generally an inverse correlation between controllability and maneuverability. For example, the omnidirectional designs such as the four-castor wheel configuration require significant processing to convert desired rotational and translational velocities to individual wheel commands. Furthermore, such omnidirectional designs often have greater degrees of freedom at the wheel. For instance, the Swedish wheel has a set of free rollers along the wheel perimeter. These degrees of freedom cause an accumulation of slippage, tend to reduce dead-reckoning accuracy, and increase the design complexity.

Controlling an omnidirectional robot for a specific direction of travel is also more difficult and often less accurate when compared to less maneuverable designs. For example, an Ackerman steering vehicle can go straight simply by locking the steerable wheels and driving the drive wheels. In a differential-drive vehicle, the two motors attached to the two

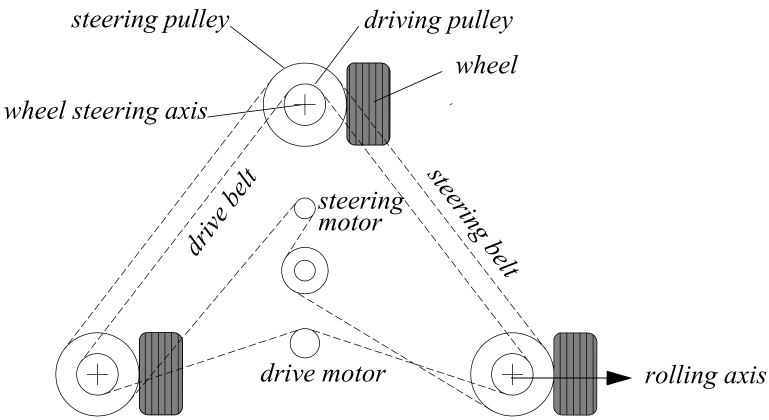


Figure 2.28
Synchro drive: The robot can move in any direction; however, the orientation of the chassis is not controllable.

wheels must be driven along exactly the same velocity profile, which can be challenging considering variations between wheels, motors, and environmental differences. With four-wheel omnidrive, such as the Uranus robot, which has four Swedish wheels, the problem is even harder because all four wheels must be driven at exactly the same speed for the robot to travel in a perfectly straight line.

In summary, there is no “ideal” drive configuration that simultaneously maximizes stability, maneuverability, and controllability. Each mobile robot application places unique constraints on the robot design problem, and the designer’s task is to choose the most appropriate drive configuration possible from among this space of compromises.

2.3.2 Wheeled locomotion: Case studies

We next describe four specific wheel configurations, in order to demonstrate concrete applications of the concepts discussed above to mobile robots built for real-world activities.

2.3.2.1 Synchro drive

The synchro drive configuration (figure 2.28) is a popular arrangement of wheels in indoor mobile robot applications. It is an interesting configuration because, although there are three driven and steered wheels, only two motors are used in total. The one translation motor sets the speed of all three wheels together, and the one steering motor spins all the wheels together about each of their individual vertical steering axes. But note that the wheels are being steered with respect to the robot chassis, and therefore there is no direct way of reorienting the robot chassis. In fact, the chassis orientation does drift over time due to uneven tire slippage, causing rotational dead-reckoning error.

Synchro drive is particularly advantageous in cases where omnidirectionality is sought. So long as each vertical steering axis is aligned with the contact path of each tire, the robot can always reorient its wheels and move along a new trajectory without changing its footprint. Of course, if the robot chassis has directionality and the designers intend to reorient the chassis purposefully, then synchro drive is appropriate only when combined with an independently rotating turret that attaches to the wheel chassis. Commercial research robots such as the Nomadics 150 or the RWI B21r have been sold with this configuration (figure 1.12).

In terms of dead reckoning, synchro drive systems are generally superior to true omnidirectional configurations but inferior to differential-drive and Ackerman steering systems. There are two main reasons for this. First and foremost, the translation motor generally drives the three wheels using a single belt. Because of slop and backlash in the drive train, whenever the drive motor engages, the closest wheel begins spinning before the furthest wheel, causing a small change in the orientation of the chassis. With additional changes in motor speed, these small angular shifts accumulate to create a large error in orientation during dead reckoning. Second, the mobile robot has no direct control over the orientation of the chassis. Depending on the orientation of the chassis, the wheel thrust can be highly asymmetric, with two wheels on one side and the third wheel alone, or symmetric, with one wheel on each side and one wheel straight ahead or behind, as shown in figure 2.22. The asymmetric cases result in a variety of errors when tire-ground slippage can occur, again causing errors in dead reckoning of robot orientation.

2.3.2.2 Omnidirectional drive

As we will see later in section 3.4.2, omnidirectional movement is of great interest for complete maneuverability. Omnidirectional robots that are able to move in any direction (x, y, θ) at any time are also holonomic (see section 3.4.2). They can be realized by using spherical, castor, or Swedish wheels. Three examples of such holonomic robots are presented here.

Omnidirectional locomotion with three spherical wheels. The omnidirectional robot depicted in figure 2.29 is based on three spherical wheels, each actuated by one motor. In this design, the spherical wheels are suspended by three contact points, two given by spherical bearings and one by a wheel connected to the motor axle. This concept provides excellent maneuverability and is simple in design. However, it is limited to flat surfaces and small loads, and it is quite difficult to find round wheels with high friction coefficients.

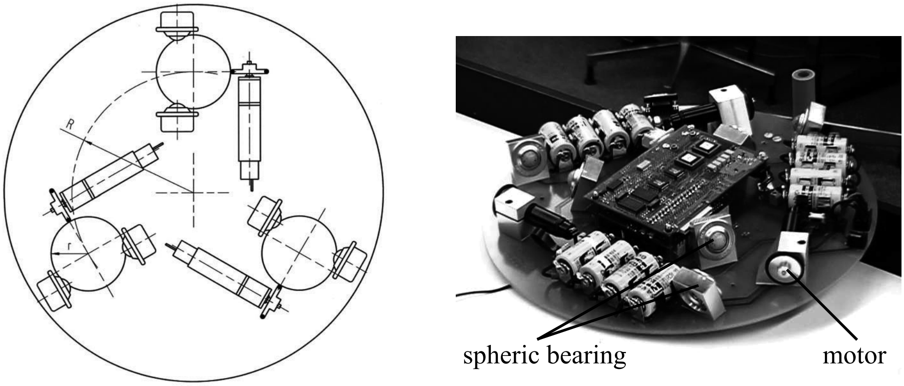


Figure 2.29
The Tribolo designed at EPFL (Swiss Federal Institute of Technology, Lausanne, Switzerland). Left: arrangement of spheric bearings and motors (bottom view). Right: Picture of the robot without the spherical wheels (bottom view).

Omnidirectional locomotion with four Swedish wheels. The omnidirectional arrangement depicted in figure 2.30 has been used successfully on several research robots, including the Carnegie Mellon Uranus. This configuration consists of four Swedish 45-degree wheels, each driven by a separate motor. By varying the direction of rotation and relative speeds of the four wheels, the robot can be moved along any trajectory in the plane and, even more impressively, can simultaneously spin around its vertical axis.

For example, when all four wheels spin "forward" or "backward," the robot as a whole moves in a straight line forward or backward, respectively. However, when one diagonal pair of wheels is spun in the same direction and the other diagonal pair is spun in the opposite direction, the robot moves laterally.

This four-wheel arrangement of Swedish wheels is not minimal in terms of control motors. Because there are only three degrees of freedom in the plane, one can build a three-wheel omnidirectional robot chassis using three Swedish 90-degree wheels as shown in table 2.1. However, existing examples such as Uranus have been designed with four wheels owing to capacity and stability considerations.

One application for which such omnidirectional designs are particularly amenable is mobile manipulation. In this case, it is desirable to reduce the degrees of freedom of the manipulator arm to save arm mass by using the mobile robot chassis motion for gross motion. As with humans, it would be ideal if the base could move omnidirectionally with-

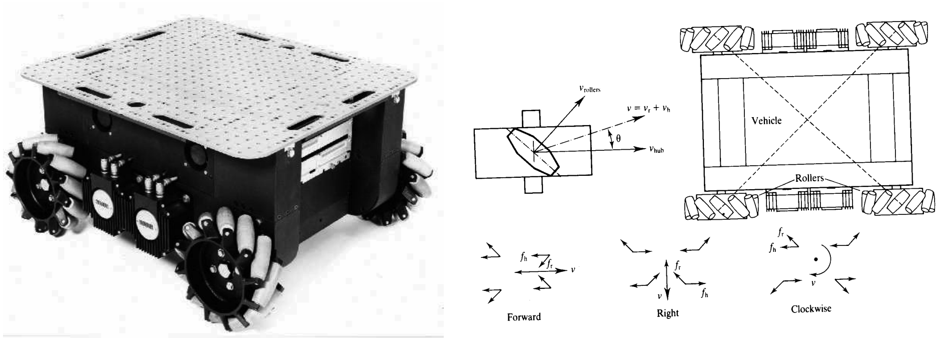


Figure 2.30
The Carnegie Mellon Uranus robot, an omnidirectional robot with four powered Swedish 45-wheels.

Figure 2.31
The Nomad XR4000 from Nomadic Technologies had an arrangement of four castor wheels for holonomic motion. All the castor wheels are driven and steered, thus requiring a precise synchronization and coordination to obtain a precise movement in x, y , and θ .

out greatly impacting the position of the manipulator tip, and a base such as Uranus can afford precisely such capabilities.

Omnidirectional locomotion with four castor wheels and eight motors. Another solution for omnidirectionality is to use castor wheels. This is done for the Nomad XR4000 from Nomadic Technologies (figure 2.31), giving it excellent maneuverability. Unfortunately, Nomadic has ceased production of mobile robots.

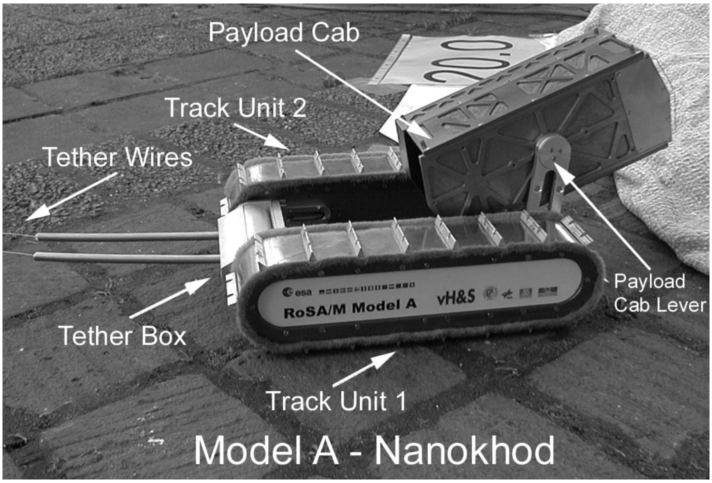


Figure 2.32
The microrover Nanokhod, developed by von Hoerner & Sulger GmbH and the Max Planck Institute, Mainz, for the European Space Agency (ESA), will probably go to Mars [302, 327].

The preceding three examples are drawn from table 2.1, but this is not an exhaustive list of all wheeled locomotion techniques. Hybrid approaches that combine legged and wheeled locomotion, or tracked and wheeled locomotion, can also offer particular advantages. Following are two unique designs created for specialized applications.

2.3.2.3 Tracked slip/skid locomotion

In the wheel configurations discussed earlier, we have made the assumption that wheels are not allowed to skid against the surface. An alternative form of steering, termed slip/skid, may be used to reorient the robot by spinning wheels that are facing the same direction at different speeds or in opposite directions. The army tank operates this way, and the Nanokhod (figure 2.32) is an example of a mobile robot based on the same concept.

Robots that make use of tread have much larger ground contact patches, and this can significantly improve their maneuverability in loose terrain compared to conventional wheeled designs. However, due to this large ground contact patch, changing the orientation of the robot usually requires a skidding turn, wherein a large portion of the track must slide against the terrain.

The disadvantage of such configurations is coupled to the slip/skid steering. Because of the large amount of skidding during a turn, the exact center of rotation of the robot is hard to predict and the exact change in position and orientation is also subject to variations depending on the ground friction. Therefore, dead reckoning on such robots is highly inac-

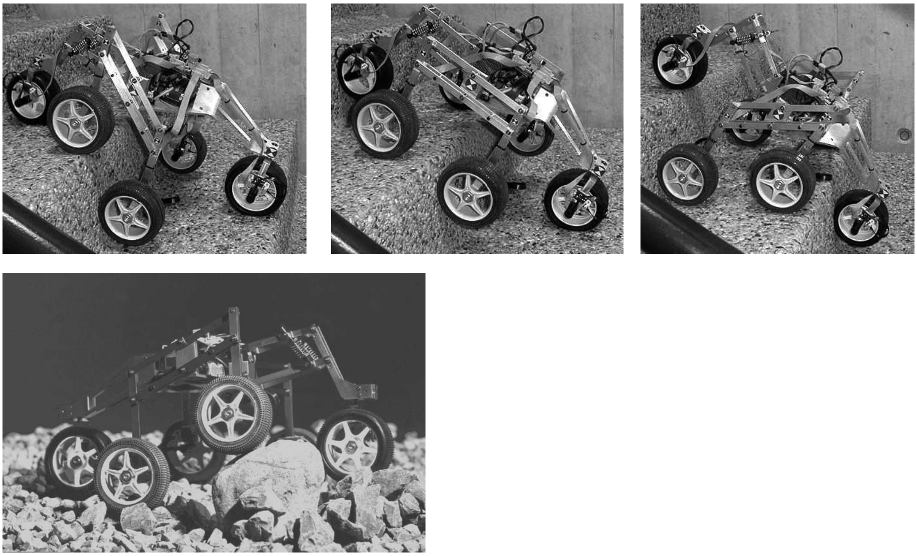


Figure 2.33
Shrimp, an all-terrain robot with outstanding passive climbing abilities (EPFL [184, 289]).

curate. This is the trade-off that is made in return for extremely good maneuverability and traction over rough and loose terrain. Furthermore, a slip/skid approach on a high-friction surface can quickly overcome the torque capabilities of the motors being used. In terms of power efficiency, this approach is reasonably efficient on loose terrain but extremely inefficient otherwise.

2.3.2.4 Walking wheels

Walking robots might offer the best maneuverability in rough terrain. However, they are inefficient on flat ground and need sophisticated control. Hybrid solutions, combining the adaptability of legs with the efficiency of wheels, offer an interesting compromise. Solutions that passively adapt to the terrain are of particular interest for field and space robotics. The Sojourner robot of NASA/JPL (see figure 1.2) represents such a hybrid solution, able to overcome objects up to the size of the wheels. A more recent mobile robot design for similar applications has been produced by EPFL (figure 2.33). This robot, called Shrimp, has six motorized wheels and is capable of climbing objects up to two times its wheel diameter [184, 289]. This enables it to climb regular stairs even though the robot is even smaller than the Sojourner. Using a rhombus configuration, the Shrimp has a steering wheel in the front and the rear and two wheels arranged on a bogie on each side. The front wheel has a spring suspension to guarantee optimal ground contact of all wheels at any time. The steer-

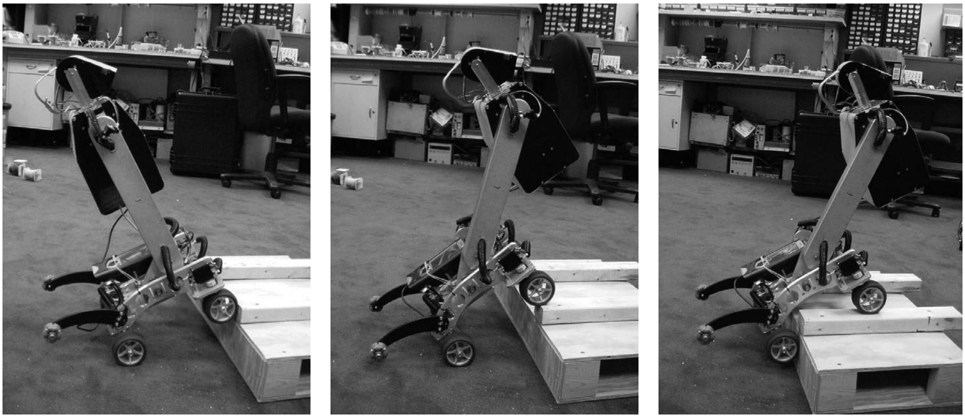


Figure 2.34
The Personal Rover, demonstrating ledge climbing using active center-of-mass shifting.

ing of the rover is realized by synchronizing the steering of the front and rear wheels and the speed difference of the bogie wheels. This allows for high-precision maneuvers and turning on the spot with minimum slip/skid of the four center wheels. The use of parallel articulations for the front wheel and the bogies creates a virtual center of rotation at the level of the wheel axis. This ensures maximum stability and climbing abilities even for very low friction coefficients between the wheel and the ground.

The climbing ability of the Shrimp is extraordinary in comparison to most robots of similar mechanical complexity, owing much to the specific geometry and thereby the manner in which the center of mass (COM) of the robot shifts with respect to the wheels over time. In contrast, the Personal Rover demonstrates active COM shifting to climb ledges that are also several times the diameter of its wheels, as demonstrated in figure 2.34. A majority of the weight of the Personal Rover is borne at the upper end of its swinging boom. A dedicated motor drives the boom to change the front/rear weight distribution in order to facilitate step-climbing. Because this COM-shifting scheme is active, a control loop must explicitly decide how to move the boom during a climbing scenario. In this case, the Personal Rover accomplished this closed-loop control by inferring terrain based on measurements of current flowing to each independently driven wheel [125].

As mobile robotics research matures, we find ourselves able to design more intricate mechanical systems. At the same time, the control problems of inverse kinematics and dynamics are now so readily conquered that these complex mechanics can in general be controlled. So, in the near future, we can expect to see a great number of unique, hybrid mobile robots that draw together advantages from several of the underlying locomotion mechanisms that we have discussed in this chapter. They will be technologically impressive, and each will be designed as the expert robot for its particular environmental niche.

2.4 Aerial Mobile Robots

2.4.1 Introduction

Flying objects have always exerted a great fascination on humans, encouraging all kinds of research and development. This introduction is written in a time at which the robotics community is showing a growing interest in micro aerial vehicle (MAV) development. The scientific challenge in MAV design, control, and navigation in cluttered environments and the lack of existing solutions is the main leitmotiv. On the other hand, the broad field of applications in both military and civilian markets is encouraging the funding of MAV-related projects. However, the task is not trivial due to several open challenges.

In the field of sensing technologies, industry can currently provide a new generation of integrated micro inertial measurement units (IMU, section 4.1.7) composed generally of micro electro-mechanical systems (MEMS) technology, inertial and magneto-resistive sensors. The latest technology in high density power storage offers about 230Wh/kg (Li-Ion technology in 2009), which is a real jump ahead, especially for micro aerial robotics. This technology was originally developed for handheld applications and is now widely used in aerial robotics. The cost and size reduction of such systems makes it very interesting for the civilian market. Simultaneously, this reduction of cost and size implies performance limitations and thus a more challenging control problem. Moreover, the miniaturization of inertial sensors imposes the use of MEMS technology, which is still much less accurate than the conventional sensors because of noise and drift. The use of low-cost IMUs demands less effective data processing and thus a bad orientation data prediction in addition to a weak drift rejection. On the other hand, and in spite of the latest progress in miniature actuators, the scaling laws are still unfavorable and one has to face the problem of actuator saturation. That is to say, even though the design of micro aerial robots is possible, the control is still a challenging goal.

Investigating relations between size and weight of flying objects yields some interesting findings. Tennekes's Great Flight Diagram [50] (figure 2.35) plots weight versus wing loading for all sizes comprising insects, birds, and sailplanes all the way up to the Boeing 747. It illustrates the fundamental simplified assumption that the weight W scales with the wingspan b to the power of three (b^3), while the wing surface S may be seen as scaling with b^2. Figure 2.35 shows Tennekes's Great Flight Diagram augmented with some unmanned solar airplanes and radio controlled airplanes [248] that are comparable to small robotic unmanned aerial systems. The curve W/S represents an average of the shown data points. Notice that different constructions still yield different results: the extremely lightweight solar airplane *Helios* by NASA, for example, with its 75 meters of wingspan and a surface

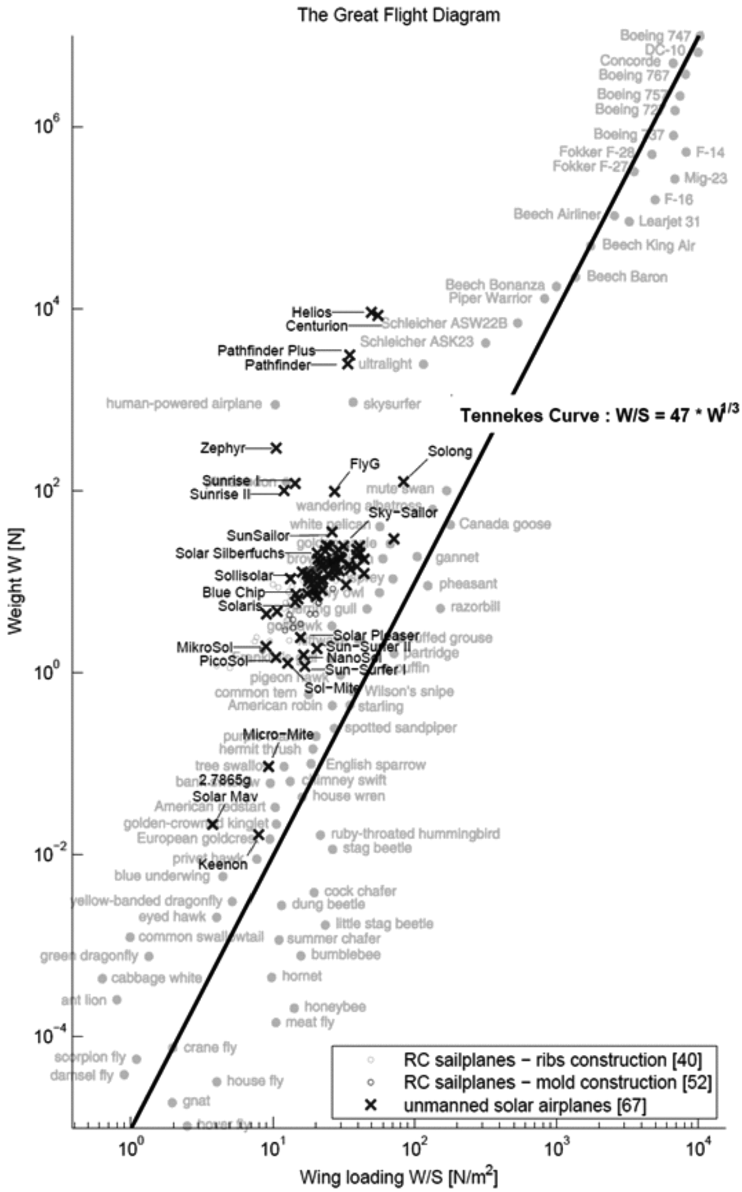


Figure 2.35 Tennekes's Great Flight Diagram [50] augmented with RC sailplanes and unmanned solar airplanes. Image courtesy of A. Noth [248].

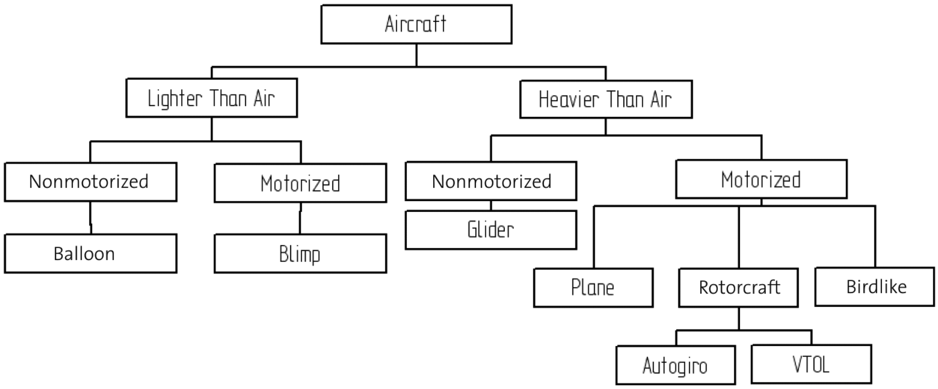


Figure 2.36 General classification of aircrafts.

area of $184 m^2$, has approximately the same wing loading as a pelican but it is heavier by a factor of 1,000 and of course is much larger.

2.4.2 Aircraft configurations

In general, aerial vehicles can be divided into two categories: Lighter Than Air (LTA) and Heavier Than Air (HTA). Figure 2.36 presents a general classification of aircraft depending on the flying principle and the propulsion mode. Table 2.2 gives a nonexhaustive comparison between different flying principles from the miniaturization point of view. From this table, one can easily conclude that Vertical Take-Off and Landing (VTOL) systems such as helicopters or blimps have an unquestionable advantage compared with the other concepts. This superiority is owed to their unique ability for vertical, stationary, and low-speed flight. The key advantage of blimps is the *autolift* and simplicity of control, which can be essential for critical applications, such as aerial surveillance and space exploration. However, VTOL vehicles in different configurations represent today one of the most promising flying concepts seen in terms of miniaturization. Figure 2.37 lists different configurations commonly used in MAV research and industry.

2.4.3 State of the art in autonomous VTOL

The state of the art in MAV research has dramatically changed in the last few years. The number of projects tackling this problem has considerably and suddenly increased. Until 2006, the main research problem was MAV stabilization, especially for mini quadrotors. Since 2007, the research community shifted its interest toward autonomous navigation, first outdoor and more recently even indoor.

Table 2.2 Flying principle comparison (1 = Bad, 3 = Good)

	Airplane	Helicopter	Bird	Autogiro	Blimp
Power cost	2	1	2	2	3
Control cost	2	1	1	2	3
Payload/volume	3	2	2	2	1
Maneuverability	2	3	3	2	1
Stationary flight	1	3	2	1	3
Low speed fly	1	3	2	2	3
Vulnerability	2	2	3	2	2
VTOL	1	3	2	1	3
Endurance	2	1	2	1	3
Miniaturization	2	3	3	2	1
Indoor usage	1	3	2	1	2
Total	19	25	24	18	25

The CSAIL laboratory at MIT is presently one of the leaders in terms of MAV navigation in GPS-denied environments. The quadrotor that it used in the 2009 edition of the AUVSI competition uses laser scanners to localize and navigate autonomously inside buildings. The quadrotor from ALU Freiburg [142] is also equipped with a laser scanner; it achieves global localization using a particle filter and a graph-based SLAM algorithm (both these algorithms will be treated in section 5.8.2). It is thus able to navigate autonomously indoors while avoiding obstacles. STARMAC, from Stanford University, targets the demonstration of multiagent control of quadrotors of about 1 kg, outdoors, using GPS. ETH Zurich is also participating in this endeavor with different projects. The European project sFly (www.sfly.org) targets outdoor autonomous navigation of a swarm of small quadrotors using monocular vision as the main sensor (no laser, no GPS). To the best of our knowledge, the smallest existing autonomous helicopter is the muFly helicopter, developed at ETH Zurich within the European project muFly (www.mufly.org): it weighs 80 g and has an overall span of 17.5 cm. In addition to an IMU, muFly is equipped with a 360-degree laser scanner, a down-looking micro camera, and a miniature omnidirectional camera that weighs less than 5 g. These projects are listed in figure 2.38.

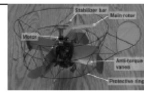
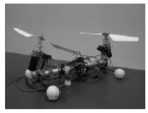
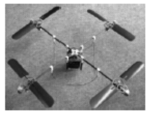
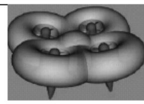
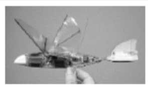
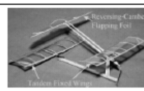
Configuration *e.g.*	Advantages	Drawbacks	Picture
Fixed-wing (AeroVironment)	Simple mechanics, silent operation	No hovering	
Single rotor (A. V de Rostyne)	Good controllability, good maneuverability	Complex mechanics, large rotor, long tail boom	
Axial rotor (Univ. of Maryland)	Simple mechanics, compactness	Complex aerodynamics	
Coaxial rotors (EPSON)	Simple mechanics, compactness	Complex aerodynamics	
Tandem rotors (Heudiasyc)	Good controllability, simple aerodynamics	Complex mechanics, large size	
Quadrotor (EPFL-ETHZ)	Good maneuverability, simple mechanics, increased payload	High energy consumption, large size	
Blimp (EPFL)	Low power, long flight operation, auto-lift	Large size, weak maneuverability	
Hybrid quadrotor-blimp (MIT)	Good maneuverability, good survivability	Large size, weak maneuverability	
Birdlike (Caltech)	Good maneuverability, compactness	Complex mechanics, complex control	
Insectlike (UC Berkeley)	Good maneuverability, compactness	Complex mechanics, complex control	
Fishlike (US Naval Lab)	Multimode mobility, efficient aerodynamics	Complex control, weak maneuverability	

Figure 2.37 Common MAV configurations.

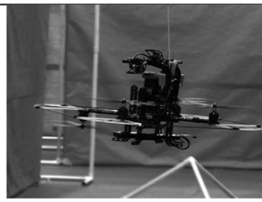
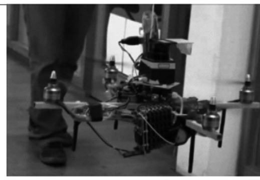
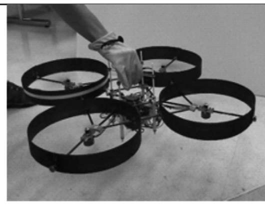
Projects	University	Status	Picture
MIT-MAV	MIT	Ended	
Freiburg MAV	ALU Freiburg	In progress	
Starmac	Stanford	In progress	
sFly	ETH Zürich	In progress	
muFly	ETH Zürich	Ended	

Figure 2.38 Progress in autonomous VTOL systems.

2.5 Problems

1. Consider an eight-legged walking robot. Consider gaits in terms of lift/release events as in this chapter. (a) How many possible events exist for this eight-legged machine? (b) Specify two different statically stable walking gaits using the notation of figure 2.8.

2. Describe two wheel configurations that enable omnidirectional motion that are not identified in section 2.3.2.2. Note that you may use any type of wheel in these two designs. Draw the configurations using the notation of table 2.1.

3. You wish to build a dynamically stable robot with a single wheel only. For each of the four basic wheel types, explain whether or not it may be used for such a robot.

4. Challenge Question.
Four-legged machines are normally not statically stable. Design a four-legged locomotion machine that is statically stable. Draw it and describe the gait used.