Chapter 1
An Overview of Robotic Mechanical Systems

1.1 Introduction

In defining the scope of our subject, we have to establish the genealogy of robotic mechanical systems. These are, obviously, a subclass of the much broader class of *mechanical systems*. Mechanical systems, in turn, constitute a subset of the more general concept of *dynamic systems*. In the end, we must have an idea of what, in general, a *system* is.

The *Concise Oxford Dictionary* defines system as a "complex whole, set of connected things or parts, organized body of material or immaterial things," whereas the *Random House College Dictionary* defines the same as "an assemblage or combination of things or parts forming a complex or unitary whole." *Le Petit Robert*, in turn, defines system as "*Ensemble possédant une structure, constituant un tout organique*," which can be loosely translated as "A structured assemblage constituting an organic whole." In the foregoing definitions, we note that the underlying idea is that of a set of elements interacting as a whole.

On the other hand, a *dynamic system* is a subset of the set of systems. For our purposes, we can dispense with a rigorous definition of this concept. Suffice it to say that, to qualify as *dynamic*, a system should be endowed with three elements, namely, a *state*, an *input*, and an *output*, in addition to a *rule of transition* from one current state to a *future* one. Moreover, the state is a *functional* of the input and a function of a *previous* state. In this concept, then, the idea of order is important, and can be taken into account by properly associating each state value with time. The state at every instant is a functional, as opposed to a function, of the input, which is characteristic of dynamic systems. This means that the state of a dynamic system at a certain instant is determined not only by the value of the input at that instant, but

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also by the past history of the input—besides, of course, its *initial state*. By virtue of this property, dynamic systems are said to have *memory*.

On the contrary, systems whose state at a given instant is only a *function* of the input at the current time are static, and said to have no memory. Additionally, since the state of a dynamic system is a result of all the past history of the input, the future values of this having no influence on the state, dynamic systems are said to be *nonanticipative* or *causal*. By the same token, systems whose state is the result of future values of the input are said to be *anticipative* or *noncausal*. In fact, we need not worry about the latter, and hence, all systems we will study will be assumed to be causal.

Obviously, a mechanical system is a system composed of mechanical elements. If this system complies with the definition of dynamic system, then we end up with a *dynamic mechanical system*. For brevity, we will refer to such systems as *mechanical systems*, the dynamic property being implicit throughout the book. Mechanical systems of this type are those that occur whenever the inertia of their elements is accounted for. Static mechanical systems are those in which inertia is neglected. Moreover, the elements constituting a mechanical system are rigid and deformable solids, compressible and incompressible fluids, and inviscid and viscous fluids.

From the foregoing discussion, then, it is apparent that mechanical systems can be constituted either by lumped-parameter or by distributed-parameter elements. The former reduce to particles; rigid bodies; massless, conservative springs; and massless, nonconservative dashpots. The latter appear whenever bodies are modeled as continuous media. In this book, we will focus on lumped-parameter mechanical systems. In mechanical systems, the driving forces and moments exerted by the *actuators* and the environment play the role of the input, the set of signals picked up by the *sensors* that of the output. Finally, the rules of transition are dictated by the laws of nature, especially from mechanics, electromagnetics and biology.

Furthermore, a mechanical system can be either natural or *engineered*,[1] the latter being the subject of our study. Engineered mechanical systems can be either controlled or uncontrolled. Most engineering systems are controlled mechanical systems, and hence, we will focus on these. Moreover, a controlled mechanical system may be *robotic* or nonrobotic. The latter are systems supplied with primitive controllers, mostly analog, such as thermostats, servovalves, etc. Robotic mechanical systems, in turn, can be *programmable*, such as most current industrial robots, or *intelligent*, as discussed below. Programmable mechanical systems obey motion commands either stored in a memory device or generated on-line. In either case, they need sensors, such as joint encoders, accelerometers, and dynamometers.

Intelligent robots or, more broadly speaking, *intelligent machines*, are yet to be demonstrated, but have become the focus of intensive research. If intelligent

[1]In the previous editions we had used the term "man-made" instead. To avoid a gender-biased terminology, we could have used "artificial," but this term, while meaning "human-made," also has a negative connotation: "lacking in natural or spontaneous quality."

machines are ever feasible, they will depend highly on a sophisticated sensory system and the associated hardware and software for the processing of the information supplied by the sensors. The processed information would then be supplied to the actuators in charge of producing the desired robot motion. Contrary to programmable robots, whose operation is limited to *structured environments*, intelligent machines should be capable of reacting to unpredictable changes in an *unstructured environment*. Thus, intelligent machines should be supplied with decision-making capabilities aimed at mimicking the natural decision-making process of living organisms. This is the reason why such systems are termed intelligent in the first place. Thus, intelligent machines are expected to *perceive* their environment and draw conclusions based on this perception. What is supposed to make these systems *intelligent* is their capability of perceiving, which involves a certain element of subjectivity. By far, the most complex of perception tasks, both in humans and machines, is visual (Levine 1985; Horn 1986).

In summary, then, an intelligent machine is expected to (a) *perceive* the environment; (b) *reason* about this perception; (c) *make decisions* based on this reasoning; and (d) *act* according to a plan specified at a very high level. What the latter means is that the motions undergone by the machine are decided upon based on instructions similar to those given to a human being, like *bring me a glass of water without spilling the water.*

Whether intelligent machines with all the above features will be 1 day possible or not is still a subject of discussion, sometimes at a philosophical level. Penrose (1994) wrote a refutal to the claim that intelligent machines are possible.

A genealogy of mechanical systems, including robotic ones, is given in Fig. 1.1. In that figure, we have drawn a dashed line between mechanical systems and other systems, both engineered and natural. This line is intended to emphasize the interaction of mechanical systems with electrical, thermal, and other systems, including the human system, which is present in telemanipulators, to be discussed below.

1.2 The General Architecture of Robotic Mechanical Systems

From Sect. 1.1, then, a robotic mechanical system is composed of a few subsystems, namely, (a) a mechanical subsystem composed in turn of both rigid and deformable bodies, although the systems we will study here are composed only of the former; (b) a sensing subsystem; (c) an actuation subsystem; (d) a controller; and (e) an information-processing subsystem. Additionally, these subsystems communicate among themselves via *interfaces*, whose function consists basically of decoding the transmitted information from one medium to another. Figure 1.2 illustrates the

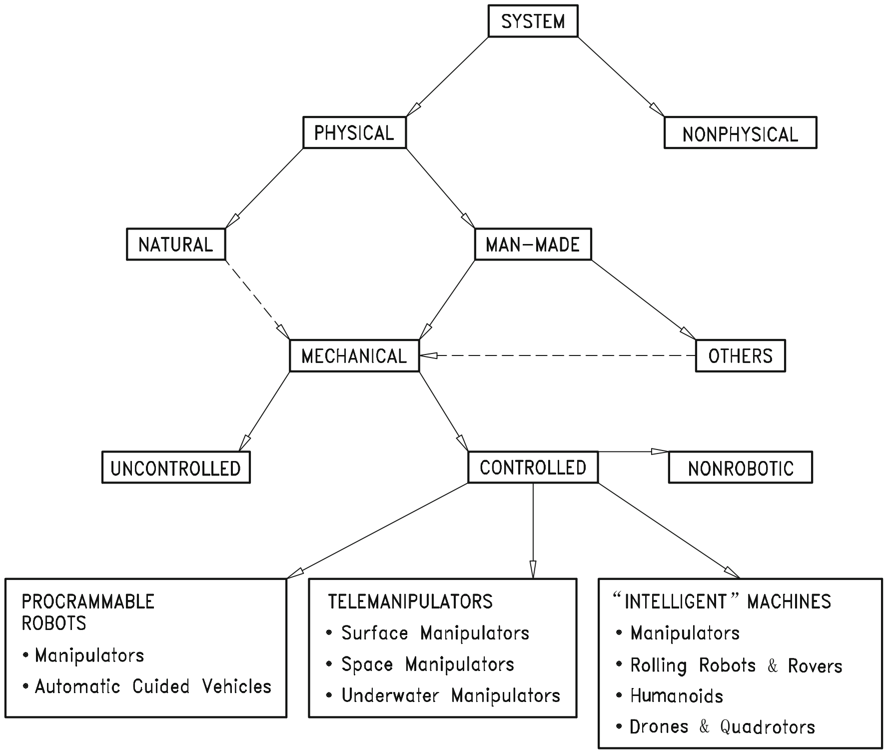
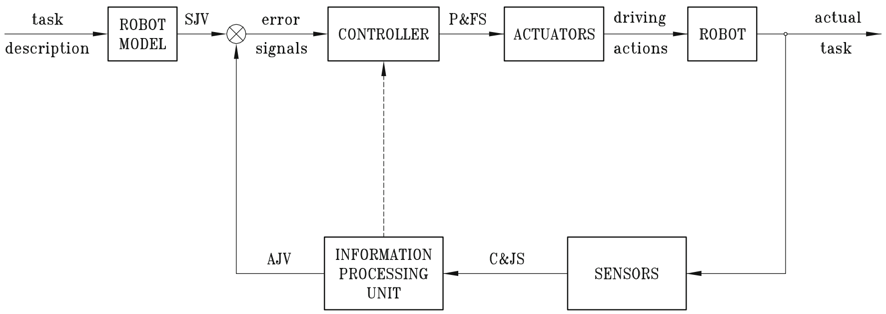


Fig. 1.1 A genealogy of robotic mechanical systems



SJV: synthesized joint variables (angles and torques)
P&FS: position and force signals
C&JS: Cartesian and joint signals
AJV: actual joint variables (angles and torques)

Fig. 1.2 General architecture of a robotic mechanical system *general architecture*[2] of a typical robotic mechanical system. The input here is a *prescribed task*, which is defined either on the spot or off-line. The former case is essential for a machine to be called intelligent, while the latter is present in programmable machines. Thus, tasks would be described to intelligent machines by a software system based on techniques of artificial intelligence (AI). This system would replace the human being in the decision-making process. Programmable robots require human intervention either for the coding of preprogrammed tasks at a very low level or for *telemanipulation*. A "very low level of programming" means that the motions of the machine are specified as a sequence of either joint motions or Cartesian coordinates associated with landmark points of that specific body performing the task at hand. The output of a robotic mechanical system is the *actual task*, which is monitored by the sensors. The sensors, in turn, transmit task information in the form of feedback signals, to be compared with the prescribed task. The errors between the prescribed and the actual task are then fed back into the controller, which further synthesizes the necessary corrective signals. These are, in turn, fed back into the actuators, which then drive the mechanical system through the required task, thereby closing the loop. The problem of robot control has received extensive attention in the literature, and will not be pursued here. The interested reader is referred to the excellent works on the subject, e.g., those of Samson et al. (1991), Khalil and Dombre (2002); and Spong et al. (2006). Of special relevance to robot control is the subject of nonlinear control at large, a pioneer here being Isidori (1989).

Robotic mechanical systems with a human being in their control loop are called *telemanipulators*. Thus, a telemanipulator is a robotic mechanical system in which the task is controlled by a human, possibly aided by sophisticated sensors and display units. The human operator replaces the `ROBOT MODEL` block in the diagram of Fig. 1.2, produces the task description, becomes a part of the sensory system, and plays a major role in the `INFORMATION PROCESSING UNIT` block. Based on the information displayed, the operator makes decisions about corrections in order to accomplish the prescribed task. Shown in Fig. 1.3 is a telemanipulator designed for space applications, namely, the *Canadarm2*, along with *DEXTRE*, the *Special-Purpose Dextrous Manipulator* (SPDM), both mounted on the *Mobile Servicing System* (MSS), a module of the *International Space Station*. Moreover, a detailed view of DEXTRE is shown in Fig. 1.4. In the manipulators of these two figures, the human operator is an astronaut who commands and monitors the motions of the robot from inside the EVA (extravehicular activity) workstation. The number of controlled axes of each of these manipulators being larger than

[2] In Chap. 4 we introduce the concept of *robotic architecture*, to indicate the *geometry* of the underlying mechanical system. We refer here to the "general architecture" of the whole robotic system, to distinguish between the two concepts.

Fig. 1.3 Canadarm2 and DEXTRE (courtesy of the Canadian Space Agency)

Fig. 1.4 DEXTRE, the special-purpose dextrous manipulator (courtesy of the Canadian Space Agency)

six, both are termed *redundant*. The challenge here is that the mapping from task coordinates to joint motions is not unique, and hence, among the infinitely many joint trajectories that the operator has at his or her disposal for a given task, an on-board processor must evaluate the best one according to a performance criterion.

1.2.1 Types of Robots by Function

When the first edition was written, in the early nineties, the classification of robots was rather straightforward, for there were mainly two kinds: serial and parallel. Nowadays a robot classification is a daunting task, by virtue of the intense activity displayed in the areas of robotics research, robot design, innovation and applications. For example, a look at the proceedings of a recent edition of the *IEEE International Conference on Robotics and Automation* will reveal a vast spectrum of robots currently working on the shopfloor, in the operating room, in rehabilitation centers, and even at home. In attempting a classification of robots, the most comprehensive criterion would be by function. We thus have a tentative, but by no means comprehensive, classification:

- Manipulators: robotic arms and hands;
- motion generators: flight simulators; SCARA (Selective-Compliance Assembly Robot Arm); and moving platforms at large;
- locomotors, a.k.a. mobile robots: legged and wheeled robots, including rovers;
- swimming robots; and
- flying robots.

We expand below on these robot types.

1.2.2 Types of Robots by Size

The most common type of robots under this criterion is macro-robots, or those whose dimensions are measured in meter. These are robots with a reach of typically a couple of meters. Shown in Fig. 1.5 is a heavy-duty robot, IRB-7600, manufactured by ABB Robotics, with a reach of 2.800 m and a load-carrying capacity of 3,332 N. This robot finds applications mainly in the manipulation of heavy parts in the automobile industry.

Micro-robots bear dimensions allowing them a reach of a fraction of a mm. For example, the robot reported by Sun et al. (2005) for MEMS (micro-electromechanical systems) assembly, features a maximum reach of 100 μm in each of two orthogonal directions and one of 50 μm in a direction orthogonal to these two.

1.2.3 Types of Robots by Application

Robot applications have widespread as much as robot architectures. Current applications span the classical industrial robots for arc-welding, for example, on to material-handling, surveillance, surgical operations, rehabilitation and entertainment.

Fig. 1.5 The IRB-7600, a heavy-duty robotic arm with a serial architecture (courtesy of ABB robotics)

1.3 Manipulators

Of all robotic mechanical systems, manipulators deserve special attention for various reasons. One is that, in their simplest form, as robotic arms, they occur most frequently in industry. Another is that the architecture of robotic arms constitutes the simplest of all robotic architectures, and hence, appear as constituents of other, more complex robotic mechanical systems, as will become apparent in later chapters. A manipulator, in general, is a mechanical system aimed at object manipulation. Manipulating, in turn, means to move something with one's hands, as the word derives from the Latin *manus*, meaning *hand*. The basic idea behind the foregoing concept is that hands are among the organs that the human brain can control mechanically with the highest accuracy, as the work of an artist like Picasso, of an accomplished guitar player, or of a surgeon can attest.

A manipulator is thus any device that helps a human operator perform a manipulating task. Although manipulators have existed ever since man created the first tool, only very recently, namely, by the end of World War II, have manipulators developed to the extent that they are now capable of actually mimicking motions of the human arm, and of the human hand, for that matter. In fact, during WWII, the need arose for manipulating probe tubes containing radioactive substances. This led to the first six-degree-of-freedom (six-dof) manipulators.

Shortly thereafter, the need for manufacturing workpieces with high accuracy arose in the aircraft industry, which led to the first numerically-controlled (NC) machine tools. The synthesis of the six-DOF manipulator and the NC machine tool produced what became the *robotic manipulator*. Thus, the essential difference between the early manipulator and the evolved *robotic* manipulator is the "robotic" qualifier, which came into the picture in the late sixties. A robotic manipulator is to be distinguished from the early manipulator by its capability of lending itself to *computer control*. While the early manipulator needed the presence of a human in the loop, to have a *master manipulator* perform a gesture, the robotic manipulator can be programmed once and for all to repeat the same task forever. Programmable manipulators owe their existence to the microprocessor. Indeed, the microprocessor, introduced in 1976 by Intel, allowed a human master to *teach* the manipulator by actually driving the manipulator itself, or a replica thereof, through a desired task, while recording all motions undergone by the master. Thus, the manipulator would later repeat the identical task by mere playback. However, the capabilities of industrial robots are fully exploited only if the manipulator is programmed with software, rather than actually driving it through its task trajectory, which many a time, e.g., in car-body spot-welding, requires separating the robot from the production line for more than a week. One of the objectives of this book is to develop tools for the programming of robotic manipulators.

Nevertheless, the capabilities offered by robotic mechanical systems go well beyond the mere playback of preprogrammed tasks. Current research aims to providing robotic systems with software and hardware that will allow them to make decisions on the spot and learn while performing a task. The implementation of such systems calls for task-planning techniques that fall beyond the scope of this book and, hence, will not be treated here. For a glimpse of such techniques, the reader is referred to the work of Latombe (1991) and the references therein.

1.3.1 Robotic Arms

Robotic manipulators first appeared as mechanical systems resembling the human arm. Robotic arms are thus constituted by a mechanical system consisting of structurally robust links coupled by either rotational or translating joints, the former being called *revolutes*, the latter *prismatic joints*. Moreover, these structures are a *concatenation* of links, thereby forming an *open kinematic chain*, with each link coupled to a predecessor and a successor, except for the two end links, which are coupled only to either a predecessor or to a successor, but not to both. The robot displayed in Fig. 1.5 is an example of a robotic arm with strong links.

Because of the *serial* nature of the coupling of links in this type of manipulator, even if they are supplied with structurally robust links, their load-carrying capacity and their stiffness is too low when compared with the other multiaxis machines, such as NC machine tools. Obviously, a low stiffness implies a low positioning accuracy.

1.3.2 Robotic Hands

Besides the hand, other mechanical subsystems constituting the human manipulation system are the arm and the forearm. Moreover, the shoulder, coupling the arm with the torso, can be regarded as a *spherical joint*, i.e., the concatenation of three revolute joints with intersecting axes. Furthermore, the arm and the forearm are coupled via the elbow, with the forearm and the hand finally being coupled by the wrist. Frequently, the wrist is modeled as a spherical joint as well, while the elbow is modeled as a simple revolute joint. Robotic mechanical systems mimicking the motions of the arm and the forearm constitute the manipulators discussed above. Here we outline more sophisticated manipulation systems that aim to produce the motions of the human hand, i.e., robotic hands. These systems are designed to perform *manipulation* tasks, a distinction being made between *simple manipulation* and *dextrous manipulation*. What the former means is the simplest form, in which the fingers play a minor role, namely, by serving as simple static structures that keep an object rigidly attached to the palm of the hand—when the palm is regarded as a rigid body. As opposed to simple manipulation, dextrous manipulation involves a controlled motion of the grasped object with respect to the palm. Simple manipulation can be achieved with the aid of a manipulator and a gripper, and need not be further discussed here. The discussion here is about dextrous manipulation.

In dextrous manipulation, the grasped object is required to move with respect to the palm of the grasping hand. This kind of manipulation appears in performing tasks that require high levels of accuracy, like handwriting or cutting tissue with a scalpel. Usually, grasping hands are multifingered, although some grasping devices exist that are constituted by a simple, open, highly redundant *kinematic chain* (Pettinato and Stephanou 1989). The kinematics of grasping is discussed in Chap. 10. The basic kinematic structure of a multifingered hand consists of a palm, which plays the role of the base of a simple manipulator, and a set of fingers. Thus, kinematically speaking, a multifingered hand has a *tree topology*, i.e., it entails a common rigid body, the palm, and a set of jointed bodies emanating from the palm. Upon grasping an object with all the fingers, the chain becomes closed, with multiple loops. Moreover, the architecture of the fingers is that of a simple manipulator, consisting of a number—two to four—of revolute-coupled links playing the role of phalanges. However, unlike manipulators of the serial type, whose joints are all independently actuated, those of a mechanical finger are not and, in many instances, are driven by one single master actuator, the remaining joints acting as slaves. Many versions of multifingered hands exist: Stanford/JPL; Utah/MIT; TU Munich; Karlsruhe; Bologna; Leuven; Milan; Belgrade; and University of Toronto, among others. Of these, the Utah/MIT Hand (Jacobsen et al. 1984, 1986) is commercially available. This hand carries four fingers, one of which is opposed to the other three and hence, plays the role of the human thumb. Each finger consists, in turn, of four phalanges coupled by revolute joints; each of these is driven by two tendons that can deliver force only when in tension, each being actuated independently. The TU

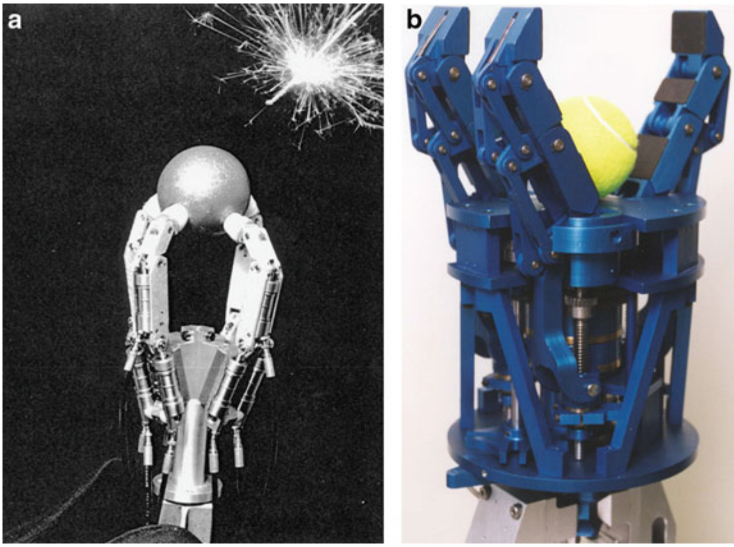


Fig. 1.6 Two instances of robotic hands: (**a**) the four-fingered hydraulically actuated TU Munich Hand (courtesy of Prof. F. Pfeiffer); and (**b**) Université Laval's, three-fingered SARAH (courtesy of Prof. C. Gosselin)

Munich Hand, shown in Fig. 1.6a, is designed with four identical fingers laid out symmetrically on a hand palm. This hand is hydraulically actuated, and provided with a very high payload-to-weight ratio. Indeed, each finger weighs only 1.470 N, but can exert a force of up to 30 N. A three-fingered hand with 12 degrees of freedom and six actuators, SARAH, was designed at Université Laval's Laboratoire de Robotique. This hand, illustrated in Fig. 1.6b, is twice as big as the human hand, weighs 88.2 N, and can hold a 686-N load (Laliberté et al. 2002).

We outline below some problems and research trends in the area of dextrous hands. A key issue here is the programming of the motions of the fingers, which is a much more complicated task than the programming of a six-axis manipulator. In this regard, Liu et al. (1989) introduced a task-analysis approach intended to program robotic hand motions at a higher level. These researchers used a heuristic, knowledge-based approach. From an analysis of the various modes of grasping, they concluded that the requirements for grasping tasks are (a) stability, (b) manipulability, (c) torquability, and (d) radial rotatability. Stability is defined as a measure of the tendency of an object to return to its original position after disturbances. Manipulability, as understood in this context, is the ability to impart motion to the object while keeping the fingers in contact with the object. Torquability, or tangential rotatability, is the ability to rotate the long axis of an object—here the authors must assume that the manipulated objects are convex and can be approximated by three-axis ellipsoids, thereby distinguishing between a long and a short axis—with a minimum force, for a prescribed amount of torque. Finally, radial rotatability is the ability to rotate the grasped object about its long axis with minimum torque about the axis.

Furthermore, Allen et al. (1989) introduced an integrated system of both hardware and software for dextrous manipulation. The system integrates force and position sensors with control commands for both the arm and the hand. To demonstrate the effectiveness of their system, the authors implemented a task consisting of removing a light bulb from its socket. Rus (1992) proposed, in turn, a paradigm allowing the high-level, task-oriented manipulation control of planar hands.

While the technological aspects of dextrous manipulation are highly advanced, theoretical aspects are still under research in this area. An extensive literature survey, with 405 references on the subject of manipulation, was given by Reynaerts (1995). But that was the state of the art in the early nineties. In the *2005 IEEE International Conference on Robotics and Automation*, there were five sessions on grasping, robotic-finger design, robotic hands and dextrous manipulation. An interesting approach to the programming of dextrous hands, *programming by demonstration*, was reported by Ekvall and Krajić (2005), under which the robotic hand is taught how to reproduce the grasping sequences of a human hand. The use of vision as a means of grasp-planning was also reported in this conference (Gockel et al. 2005).

1.4 Motion Generators

Under this heading we include robotic systems designed to produce a certain class of motions for various purposes, ranging from manipulation tasks, e.g., the positioning of a camera for surveillance, to the orientation of a surgeon's scalpel, on to moving platforms for pilot training, as in flight simulators, or for entertainment, to give people the realism of an earthquake or a roller-coaster, or simply of following a musical rhythm. Many a motion generator is supplied with a parallel architecture, as described below.

1.4.1 Parallel Robots

Parallel robots were originally proposed to cope with the problems encountered with their serial counterparts (Merlet 2006), namely, a limited load-carrying capacity, low accuracy, and low stiffness. This kind of robot was thus introduced to withstand higher payloads with lighter links. In a parallel robot, we distinguish one *base platform*, one *moving platform*, and various *legs* or *limbs*. Each leg is, in turn, a kinematic chain of the serial type, whose end-links are the two platforms. Contrary to serial robots, all of whose joints are actuated, parallel robots are supplied with unactuated joints, which brings about a substantial difference between the two types. The presence of unactuated joints makes the analysis of parallel manipulators, in general, more complex than that of serial robots.

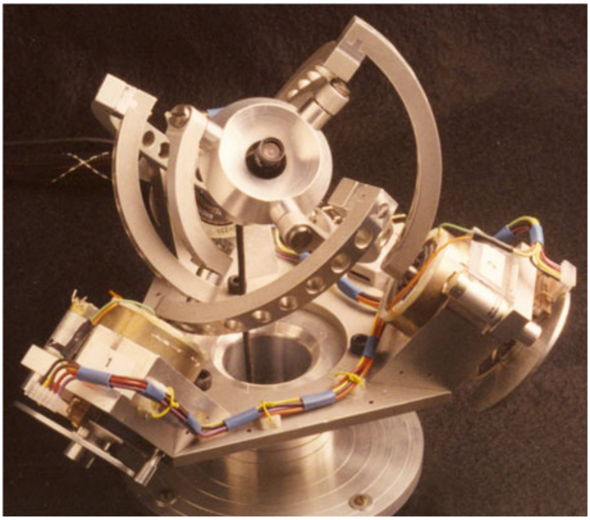


Fig. 1.7 Université Laval's Agile Eye, a three-degree-of-freedom spherical robot with a parallel architecture (courtesy of Prof. Clément Gosselin)

A paradigm of parallel manipulators is the flight simulator, consisting of six legs actuated by hydraulic pistons. The flight simulator with this architecture motivated the early work, starting in the late eighties, on parallel robots. Recently, an explosion of novel designs of parallel robots has occurred, aimed at fast manipulation tasks. An example of these robots, departing from the architecture of flight simulators, is Université Laval's Agile Eye, depicted in Fig. 1.7. This robot is designed with one fixed base and one moving platform, that carries a small camera. Base and platform are coupled by means of three identical legs, each composed of two links and three revolute joints.[3] Moreover, the axes of all nine revolutes intersect at one single point, the center of the mechanical system. For this reason, all robot links move, with respect to the base, under pure rotation, with the robot center remaining fixed. All three direct-drive motors are mounted on the base, and actuate the proximal links of the legs. This robot can reportedly produce angular velocities of the camera as high as 1,000°/s and angular accelerations of $20{,}000^\circ/\mathrm{s}^2$.

Other parallel robots have been designed for fast assembly operations, e.g., the Delta robot (Clavel 1988), developed at the Lausanne Federal Polytechnic Institute (EPFL). The Delta robot was designed to produce pure translations of its end-platform in 3D space. An instance of this robot, enhanced with a fourth joint of vertical axis, the FlexPicker, is shown in Fig. 1.8. This robot is designed with three identical legs, hanging from the ceiling, which is the robot base. Each leg carries one proximal link, coupled to the base by a revolute, which is actuated by the leg-motor. Furthermore, this link is coupled to the end-plate by means of two revolutes and

[3] It can be appreciated in Fig. 1.7 that the proximal links are made up of two curved beams, each with an axis in the form of one-quarter of a circle. These two beams are rigidly fastened, with their planes forming a 90° dihedral angle.

Fig. 1.8 FlexPicker, a realization of EPFL's Delta Robot (courtesy of ABB Robotics)

one novel kinematic pair, the Π-pair, which is nothing but a parallelogram four-bar linkage, the Π-pair being located between the two revolutes. It is noteworthy that the FlexPicker is supplied with one additional actuated joint, at the interface between the moving platform of the original Delta Robot and the gripper, appearing in the figure as a cylindrical piece. This revolute is actuated from the base by means of a transmission mechanism stemming from the center of the base in the figure.

Other instances of parallel robots can be cited: Hexa (Pierrot et al. 1991), developed at Université de Montpellier, as a six-degree-of-freedom extension of Clavel's Delta Robot; Star (Hervé and Sparacino 1992), developed at *Ecole Centrale* of Paris; the *Trussarm*, developed at the University of Toronto Institute of Aerospace Studies (UTIAS), shown in Fig. 1.9a (Hughes et al. 1991); INRIA's *main gauche*, or left hand, developed by Merlet (2006)[4] and shown in Fig. 1.9b, which is used as an aid to another robot, possibly of the serial type, to enhance its dexterity; and McGill University's parallel manipulator, intended as a shoulder module for

[4]INRIA is France's *Institut National de Recherche en Informatique et en Automatique*, the left hand, and other parallel robots having been developed at INRIA's center at Sophia-Antipolis, France.

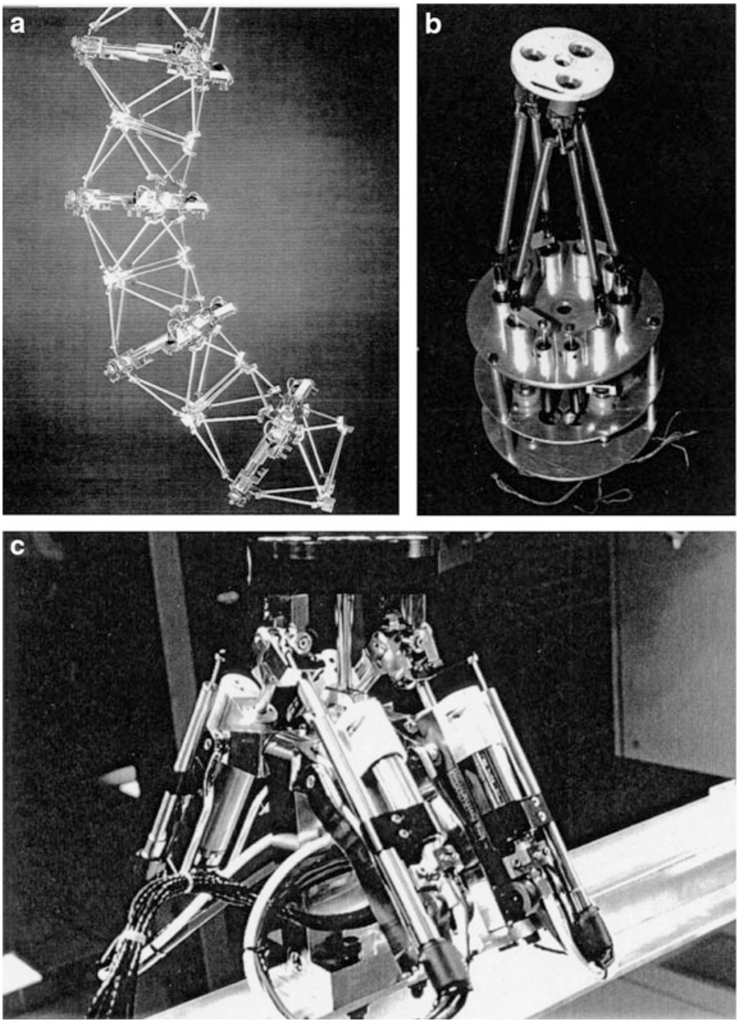


Fig. 1.9 A sample of parallel manipulators: (**a**) the UTIAS Trussarm (courtesy of Prof. P. C. Hughes); (**b**) the Merlet left hand (courtesy of Dr. J.-P. Merlet); and (**c**) the Hayward shoulder module (courtesy of Prof. V. Hayward)

orientation tasks (Hayward 1994), and capable of three-degree-of-freedom motions, produced by four hydraulic actuators, which gives the robot *redundant actuation*—Fig. 1.9c.

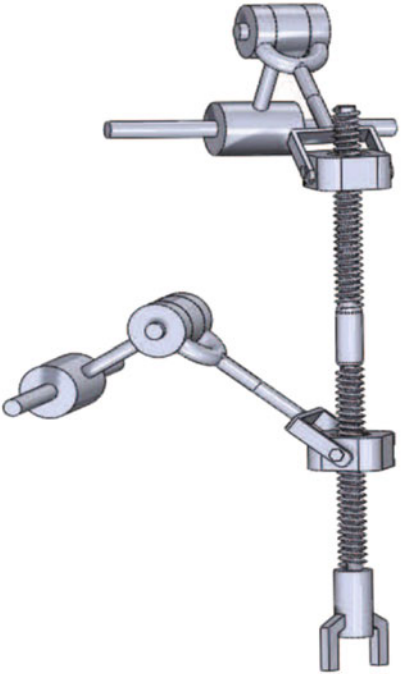
1.4.2 SCARA Systems

SCARA is an acronym standing for *Selective-Compliance Assembly Robot Arm*, as coined by Hiroshi Makino (Makino and Furuya 1980), the inventor of this new class of robots. The class was proposed as a means to provide motion capabilities to the end-effector that are required by the assembly of printed-board circuits and other electronic devices with a flat geometry. Motions consist of three independent translations and one rotation about an axis of fixed orientation, usually vertical. These robots have received special attention because of their special structure, offering an extremely high stiffness about two axes of tilting—the axes normal to the axis of rotation. The first robots of this kind appeared with a serial architecture, involving three revolutes and one prismatic joint, the latter being located either at the base or at the end-effector. These robots have attained impressive performance, capable of cycle times of 500 ms or lower, for a standard pick-and-place operation consisting of: (a) upwards translation of 25 mm; (b) horizontal translation of 300 mm, concurrently rotating through an angle of 180°; and (c) downwards translation of 25 mm. The cycle is closed by returning to the original posture following exactly the same displacement program, but in the reverse order.

Given the serial architecture of most SCARA systems, it appears that the cycle times are extremely difficult to cut further and the load-carrying capacity is equally difficult to increase. This state of affairs has motivated the emergence of alternative architectures, such as parallel or hybrid (serial-parallel). For example, Fanuc's M410iB and ABB Robotics' FlexPicker, shown in Fig. 1.8, feature hybrid SCARA architectures with long reaches, of around 3 m and payloads of above 2000 N. The manufacturers did this by means of parallelogram linkages capable of transmitting torque and motion from a common base, turning about a vertical axis, to two horizontal revolute joints, the fourth revolute having a vertical axis. Interestingly, although these robots are medium-to-heavy-duty SCARAs, the manufacturers bill them as "palletizing robots," with no relation to SCARAs. As a matter of fact, SCARAs can be regarded as generators of the Schönflies displacement subgroup (Bottema and Roth 1979; Hervé 1999). For this reason, SCARA systems are currently referred to as *Schönflies-motion generators*.

In yet another attempt to overcome the natural limitations of serial SCARAs, parallel architectures have been proposed: H4, a four-limb Schönflies-motion generator developed at France's Université de Montpellier (Company et al. 2001); the four-limb robot driven with actuated prismatic joints developed at *Institut Français de Mécanique Avancée* (Gogu 2004); and the *McGill SMG* developed at McGill University (Al-Widyan and Angeles 2004), that features only two limbs. However, this robot is overconstrained, besides exhibiting a rather limited rotatability of its moving platform. An alternative two-limb parallel SCARA was proposed recently that features an isostatic kinematic chain (Lee and Lee 2010), thereby allowing for assembly even in the presence of non-negligible machining and manufacturing errors. The architecture of this robot is illustrated in Fig. 1.10, which features two cylindrical pairs—two-degree-of-freedom (two-dof) joints that produce rotation about an axis and translation in a direction parallel to the axis—as drive units, to produce Schönflies motions. The gripper is rigidly fastened to a rod with two screws at the ends, of different pitches.

Fig. 1.10 An isostatic two-limb robot capable of SCARA motions



1.5 Locomotors

Under *locomotors* we include all robots capable of displacing themselves on a surface without any attachment to the surface. Here we distinguish two kinds of robots, legged and wheeled, as outlined below.

1.5.1 Legged Robots

A common architecture of walking machines is the hexapod, examples of which are the Ohio State University (OSU) Hexapod (Klein et al. 1983) and the OSU Adaptive Suspension Vehicle (ASV) (Song and Waldron 1989). A six-legged walking machine with a design that mimics the locomotion system of the *Carausius morosus* (Graham 1972), also known as the *walking stick*, was developed at the Technical University of Munich (Pfeiffer et al. 1995). A prototype of this machine, known as the *TUM Hexapod*, is displayed in Fig. 1.11. The legs of the TUM Hexapod are operated under neural-network control, which gives them a reflex-like response when encountering obstacles: upon sensing an obstacle, the leg bounces back and tries again to move forward, but raising the foot to a higher level. Other legged robots worth mentioning as pioneers are the Sutherland, Sprout and Associates Hexapod (Sutherland and Ullner 1984), the Titan series of quadrupeds (Hirose et al. 1985) and the Odetics series of axially symmetric hexapods (Russell 1983).

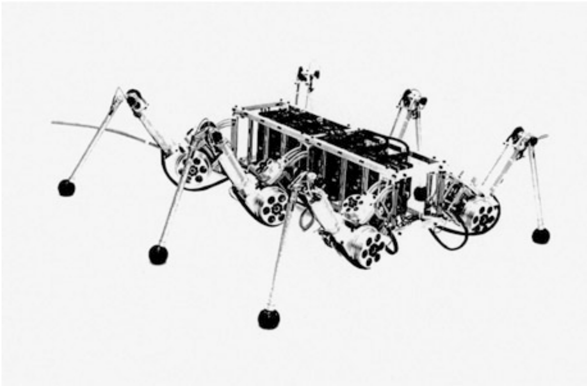


Fig. 1.11 A prototype of the TU Munich Hexapod (courtesy of Prof. F. Pfeiffer. Reproduced with permission of TSI Enterprises, Inc.)

Surveys of walking machines, of historical interest now, are those of Todd (1985) and the special issue of *The International Journal of Robotics Research* (Vol. 9, No. 2).

Walking machines appear as the sole means of providing locomotion in highly unstructured environments. In fact, the unique adaptive suspension provided by these machines allows them to navigate on uneven terrain. However, walking machines cannot traverse every type of uneven terrain, for they are of limited dimensions. Hence, if terrain irregularities such as a crevasse wider than the maximum horizontal leg reach or a cliff of depth greater than the maximum vertical leg reach are present, then the machine is prevented from making any progress. This limitation, however, can be overcome by providing the machine with the capability of attaching its feet to the terrain in the same way as a mountain climber goes up a cliff. Moreover, machine functionality is limited not only by the topography of the terrain, but also by the terrain constitution. Whereas hard rock poses no serious problem to a walking machine, muddy terrain can hamper its operation to the point that it may jam the machine. Still, under such adverse conditions, walking machines offer a better maneuverability than other vehicles. Recent work at McGill University[5] on legged locomotion has led to robots with robust designs allowing them to negotiate mud and even ponds. A series of hexapods, under the name RHEX, has been developed with these features, as shown in Fig. 1.12. The same robot is shown in Fig. 1.13 roaming a patterned floor, of about 500 mm in length, to give a clue on its dimensions.

Humanoids

An important class of legged robots is that of humanoids. Pioneer work by Vukobratovic and Stepanenko (1972) has led to modern bipeds exhibiting impres-

[5]Originally led by Prof. Martin Buehler.

Fig. 1.12 RHEX, a six-legged robot (courtesy of G. Dudek, McGill University)

Fig. 1.13 RHEX walking on a patterned floor, to indicate its dimensions (courtesy of G. Dudek, McGill University)

sive performance. Indeed, work initiated in 1986 at Honda led to ASIMO, a robotic mechanical system integrating both manipulation and locomotion in one single unit.

Research in humanoids is quite intensive at the moment, with multiple sessions on the subject during the annual *IEEE International Conference on Robotics and Automation*, including controls, motion-planning, design, voice-mimicry, and human-robot interaction.

1.5.2 Wheeled Robots and Rovers

Robots in this category are systems evolved from earlier systems called *automatic guided vehicles*, or AGVs for short. AGVs in their most primitive versions are four-wheeled, electrically powered vehicles that perform moving tasks with a certain degree of autonomy. However, these vehicles are usually limited to motions along predefined tracks that are either railways or magnetic strips glued to the ground.

The most common rolling robots use conventional wheels, i.e., wheels consisting basically of a pneumatic tire mounted on a hub that rotates about an axle fixed to the robot platform. Thus, the operation of these machines does not differ much from that of conventional terrestrial vehicles. An essential difference between rolling robots and other robotic mechanical systems is the kinematic constraints between wheel and ground in the former. These constraints are of a type known as *nonholonomic*, as discussed in detail in Chap. 12. Nonholonomic constraints are kinematic relations between point velocities and angular velocities that cannot be integrated in the form of algebraic relations between translational and rotational displacement variables. The outcome of this lack of integrability leads to a lack of a one-to-one relationship between Cartesian variables and joint variables. In fact, while angular displacements read by joint encoders of serial manipulators determine uniquely the position and orientation of their end-effector, the angular displacement of the wheels of rolling machines do not determine the position and orientation of the vehicle body. As a matter of fact, the control of rolling robots bears common features with the redundancy-resolution of manipulators of the serial type at the joint-rate level. In these manipulators, the number of actuated joints is greater than the dimension of the task space. As a consequence, the task velocity does not determine the joint rates. Not surprisingly, the two types of problems have been solved using the same tools, namely, differential geometry and Lie algebra (De Luca and Oriolo 1995).

As a means to supply rolling robots with three-dof capabilities, not found in conventional terrestrial vehicles, omnidirectional wheels (ODWs) have been developed. Examples of ODWs bear names such as *Mekanum* wheels, *Swedish wheels*, *ilonators*, or others. ODWs consist of a hub with rollers on its periphery that roll freely about their axes, the latter being oriented at a constant angle with respect to the hub axis. Rolling robots with ODWs are, thus, three-dof vehicles, and hence, can translate freely in two horizontal directions and rotate independently about a vertical axis. However, like their two-dof counterparts, three-dof rolling robots are also nonholonomic devices, and thus, pose the same problems for their control as the former. The kinematics and dynamics of robots with ODWs are studied in Sects. 10.5.2 and 12.5.2, respectively.

Further developments in the technology of rolling robots have been reported that incorporate alternative types of ODWs. For example, Killough and Pin (1992) developed a rolling robot with what they call *orthogonal ball wheels*, consisting of spherical wheels that can rotate about two mutually orthogonal axes. Borenstein (1993) proposed a mobile robot with four degrees of freedom; these were achieved with two chassis coupled by an extensible link, each chassis being driven by two actuated conventional wheels. West and Asada (1995), in turn, designed a rolling robot with *ball wheels*, i.e., balls that act as omnidirectional wheels; each ball is mounted on a set of rollers, one of which is actuated; hence, three such wheels are necessary to fully control the vehicle. The unactuated rollers serve two purposes, i.e., to provide stability to the wheels and the vehicle, and to measure the rotation of the ball, thereby detecting slip.

Fig. 1.14 QUASIMORO, a quasiholonomic mobile robot

Mobile Wheeled Pendulums

A new class of wheeled robots has emerged since the turn of the century. This class, known as *mobile wheeled pendulums* (MWP), comprises two coaxial wheels and an intermediate body, the challenge being to control both the motion of the common wheel axis and that of the intermediate body. Interest on the subject was probably promoted by the US patent behind the Ginger and the Segway Human Transporter projects. Another mobile inverted pendulum is known as JOE. More recently, a new class of nonholonomic mechanical systems was found that lies somewhat between holonomic and nonholonomic systems; these systems were thus termed *quasiholonomic* (Ostrovskaya and Angeles 1998). A realization of this class was reported by Salerno and Angeles (2004), featuring *Quasimoro*, shown in Fig. 1.14, a quasiholonomic mobile robot intended as a service robot for the motion-impaired. Quasimoro's central body is to carry food, drinks and books to the user. This robot also falls within the category of MWP. A feature common to this category, that is not encountered in other wheeled robots, is that their central body, which plays the role of the robot platform, can rotate about the wheel axis. This motion should be controlled, thereby leading to a new challenging problem, which is the stabilization of the central body, aside the classical control problem due to nonholonomy.

1.5.2.1 Rovers

Yet another class of wheeled mobile robots is known as *rovers*. These differ from other wheeled robots in that they are intended for uneven, unstructured terrain, like that found off-road on the Earth, on the Moon and on Mars. The latest high-profile rover is NASA's *Curiosity*, launched from Cape Canaveral on November 26, 2011, having landed on Mars on August 6, 2012. As rovers are intended for extraterrestrial exploration, their wheels are not expected to roll without slipping; instead, they are

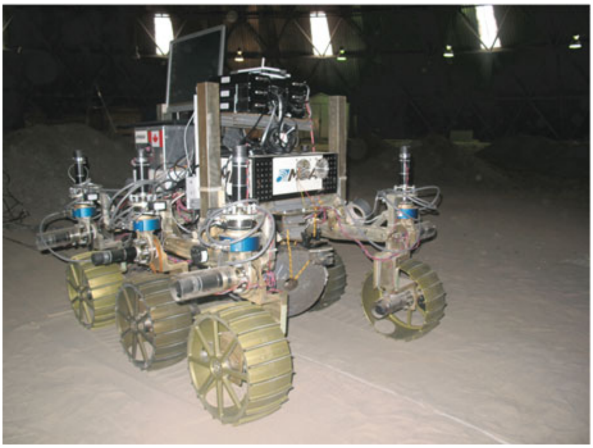


Fig. 1.15 Rover Chassis Prototype (RCP) undergoing tests at the University of Toronto Institute for Aerospace Studies (UTIAS)Mars Dome (courtesy of MDA Corporation, Brampton, ON)

Fig. 1.16 A computer model of the Sojourner, produced with Vortex (image courtesy of CM Labs Simulations Inc.)

designed to provide enough traction in the presence of soft, dry terrain. To this end, the rover wheels are supplied with grousers, i.e., crests protruding from the periphery of metal wheels. A prototype produced by MDA for planetary exploration is displayed in Fig. 1.15, showing its six wheels, all supplied with grousers. A challenge in the development of planetary rovers lies in that tests on the environment on which rovers are intended to roam are not possible. Conditions are emulated on the Earth that try to mimic the Moon's or Mars's *regolith*. One instance is the UTIAS Mars Dome—see Fig. 1.15. Moreover, the mechanics of wheel–soil interaction can only be simulated with suitable software. CM Labs' *Vortex* was used to produce the model of the Sojourner depicted in Fig. 1.16. Using this model, a novel approach was introduced to represent the wheel–soil interaction, that is based on plasticity theory (Azimi et al. 2012).

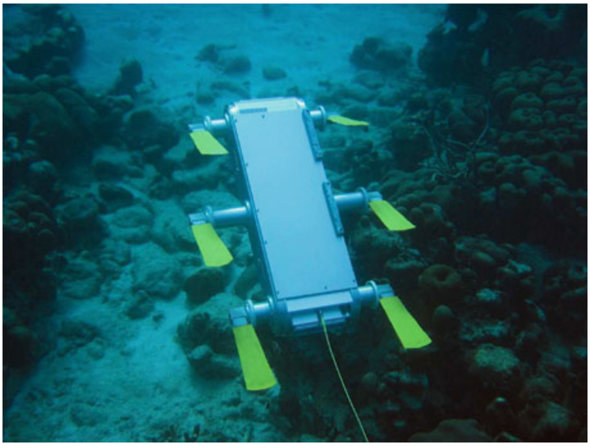


Fig. 1.17 Aqua, an amphibious robot (courtesy of G. Dudek/M. Jenkin on behalf of the Aqua Project)

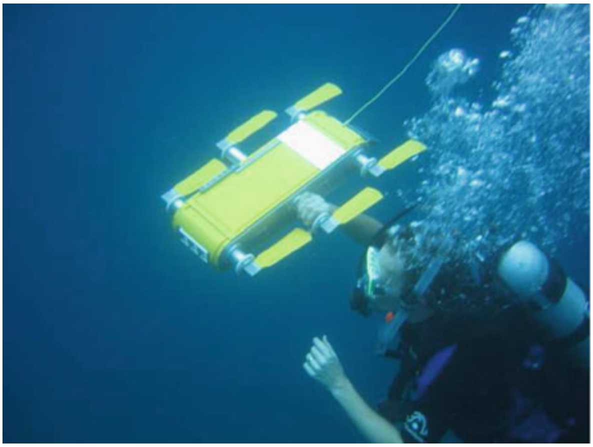


Fig. 1.18 Aqua, swimming under monitoring by its designer (courtesy of G. Dudek/M. Jenkin on behalf of the Aqua Project)

1.6 Swimming Robots

A novel class of robots with swimming capabilities is currently under development in various research laboratories. Some of these robots have been designed with the morphology of fish (Wen et al. 2011). One swimming robot designed with a hexapod morphology, featuring six flippers in lieu of legs is *Aqua*, developed at McGill University, and depicted in Figs. 1.17 and 1.18. The latter shows Aqua with its designer, Chris Prahacs.

1.7 Flying Robots

This field is becoming quite active, with some robots mimicking the morphology of insects, and falling into the category of micro-robots Hines et al. (2011); other flying robots are designed as unmanned aerial vehicles (UAV) Thorne and Yim (2011). Intensive research is now being reported in the design and control of two novel types of UAVs, namely, drones and quadrotors. The control of drones undergoing fast manuevers has been made possible by the inception of gyro-free inertial measurement systems fabricated with MEMS[6] technology. Highly maneuverable quadrotors, especially suitable for surveillance and reconnaissance missions, are small-size, light-weight flying machines supplied with "two pairs of counter-rotating rotors and propellers, located at the vertices of a square frame" (Lee et al. 2010). A recent issue of IEEE's *Robotics & Automation Magazine*—Vol. 19, No. 3, September 2012—includes a state-of-the-art account of quadrotor technology.

1.8 Exercises

The exercises included below are intended to familiarize the uninitiated reader with the issues involved in robotics, especially in the area of robotic mechanical systems. A major issue, regrettably quite often overlooked, is terminology. In attempting to work out these exercises, the beginner should be able to better understand the language of robotics and realize that a common terminology is not yet available. Some exercises are provided as an aid to either recall or learn fundamental computational issues that are extremely useful in the development of algorithms for the analysis, simulation and control of robotic mechanical systems.

1.1 List some definitions of *machine*, say about half a dozen, trying to cover the broadest timespan to date. *Hint: Hartenberg and Denavit (1964) list a few bibliographical references.*
1.2 Try to give an answer to the question: *Are intelligent machines possible?* Express your own ideas and explore what scientists like Penrose (1994) think about this controversial issue.
1.3 What is the difference among *machine*, *mechanism*, and *linkage*? In particular, analyze critically the definitions given by authorities, such as those found in the most respected dictionaries, encyclopedias, and archival documents of learned societies, e.g., the complete issue of Vol. 38, Nos. 7–10 (2003) of *Mechanism and Machine Theory* on Standardization of Terminology.
1.4 What is artificial intelligence? What is fuzzy logic? Can the techniques of these fields be applied to robotics?

[6]Microelectromechanical systems.