Chapter 2
Historical and Modern Perspective of Walking Robots

Abstract Study of historical evolution and modern point of view on a complex subject like robotics invokes motivations and professionalisms among the researchers. Research on walking machines started at the time of Leonardo da Vinci and that ultimately culminated into the development of the modern walking robots through the transformations and refinements of the ideas and design methodology over the centuries. Obviously, the allied technology of mechatronics, particularly for sensing, actuation, and control, available at various points of time in the past influenced the design and implementation of walking robot quite heavily. The urge for mimicking the walking creatures in the past and the various efforts to apply the knowledge gathered from the observations of the biological world in the design and control of walking robots has added a new dimension as well as posed many new challenges in the walking robot research. However, the various challenges faced during the design and implementation of walking robots in the past and lessons learned from them to overcome those challenges enriched the technology of walking robot and drove it toward maturity. Therefore, the knowledge of the historical evolution of walking robotics research and its modern point of view will definitely inspire a robotics researcher for undertaking new challenges for the design and development of walking robots and will also guide him to take correct design decision. This chapter presents the historical evolution of walking robots and its perspective in a condensed manner.

2.1 Introduction

The locomotion over a hard or soft solid surface by means of one or more limbs or legs can be defined as walking [1]. Walking in various forms observed among the insects and legged animals has always fascinated the mankind since the ancient time [2]. The hopping motion of kangaroo, dynamically stable locomotion of human, trotting and galloping motion of horse, statically as well as dynamically stable locomotion of quadruped animals, hexapod locomotion of cockroach and crabs,

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and multi-legged locomotion(with more than six legs)of centipedes and millipedes motivated him to understand the underlying science of legged locomotion. They observed that legs are the most feasible solution for locomotion in the natural terrains consisting of obstacles like large rocks, loose soil, deep ravines, and steep slopes, because legged animals can avoid small obstacles by making discrete contacts and passing up undesirable footholds, can climb over obstacles and step across ditches, and can also get through terrain discontinuities of body scale while maintaining the body leveled and stable. Although wheels and wheeled vehicles were established technology since ancient time of human civilization, since then people were also curious to learn the technology of legged locomotion for conquering the rough terrain with walking machines. However, it took many centuries to develop at least a walking mechanism due to lack of the knowledge of mechanics and mechanism of legs and coordination and control associated with legged locomotion.

There is a long history associated with the evolution of walking machines [3–6]. From the ancient time, mankind was curious about development of artifacts that resembles to the animals and human. Mechanically powered walking machines and mechanisms in the disguise of animals and humanlike appearance can be traced back during the era of Greek civilization. Conceptual design and sketches of artificial systems and mechanisms capable of humanlike locomotion appeared in Europe during the time of renaissance. The artifacts that were materialized from their conceptual design mainly depended on complex mechanical systems comprising of many linkages, gears, cams, shafts, etc. for the control and coordination of the legs during the locomotion. This trend continued even after a decade of the Second World War. The walking robot technology was revolutionized with the application of computer and electronic circuits for the control and coordination of legs and generation of gaits for terrain adaptive locomotion. More and more advanced walking robots were later developed with the advancement of various branches of science and technology. With the present state of the art, the day is not very far when a fully autonomous and intelligent robot will become a part of the family to serve and give company to the human after complying with the social norms [37].

From the ancient era till the present time, the continuous efforts devoted by mankind for mimicking the walking creatures for the design and control of walking robots have added a new dimension as well as posed many new challenges in the walking robot research. However, lessons learned from the various challenges faced during the design and implementation of walking robots in the past while applying the knowledge gathered from the observations of the biological world and the techniques invented to mitigate those challenges enriched the technology of walking robot and drove it toward maturity. Therefore, the knowledge of the historical evolution of walking robotics research and its modern perspective will guide a robotics researcher in the proper direction during the design and development of walking robots as well as inspire and motivate him to undertake new challenges with professionalism.

2.2 Historical Perspective of Walking Robots

Like many other branches of engineering, the legged robotics research also emerged from imagination and innovative ideas and then refinements through prototyping and experimentations. In this section, we will give a concise historical account of the thoughts and ideas as well as the development of engineering of legged robot at various times in a chronological order. At first we will describe the emergence of artificial legged locomotion from imagination and ideas during the ancient times. Then we will give a chronological portrayal of the evolution of the technology of walking robots till the present time.

2.2.1 Emergence of Artificial Legged Locomotion from Ancient Civilizations: Imagination, Ideas, and Implementations

The interest to understand the technicalities of legged locomotion observed in nature and the efforts to replicate them to mobilize the artifacts by leg mechanisms have been mentioned in the mythology and ancient scripts from the ancient Greek, Indian, Egyptian, and Chinese civilization [2]. Although no technical details of the design and development of these ancient walking devices and the associated mechanisms are available, the imagination and ideas propounded by them are quite interesting and stimulating. These ideas, although not always emerged from the principles of physical science but from the common sense and the applied knowledge of craftsmanship, were pioneering in the history of the development of walking machines and sowed the seed of legged robotics research.

Homer (VIII c. BC) mentioned about one of the Greek gods in his great epic Iliad who built humanlike and many other different types of walking devices. Descriptions of mechanical elephants have been found in ancient Indian scripts [2]. A mechanical wooden dog dated around XX c. BC has been discovered from the Egyptian pyramids. Mimicking human and animal motions for creating artificial moving figures started in the society of ancient civilized nations around the Mediterranean region for decoration of the water organs and water clocks. Ctesibius (c. 270 BC), a genius and Greek engineer, was the precursor of creating this type of devices and applied his knowledge on pneumatics and hydraulics to produce the organ and water clocks with moving figures [3, 7]. His inventions of various types of moving figures, mimicking human and animal motions, were later complied by his student Philo of Byzantium (c. 200 BC) in his book “Mechanical Collection.” Hero (c. 85 AD), a genius from Alexandria, was influenced by the practical works of Ctesibius and wrote the first well-documented technical account on realizable robots: “On Automatic Theaters,” “On Pneumatics,” and “On Mechanics” [3]. He put forward the theaters with moving inanimate figures and was the precursor of entertainment robotics. The Greeks named these machines as “automatos” meaning "machine that imitates the figure and movements of an animate being," and it is believed that the current word automation has been originated from this word [8].

A wooden walking machine known as *Mu Niu Lu Ma* was built in the III c. AD in Sichuan province of China, under the supervision of a Chinese officer Zhu Ge-Liang during the preparation for the war against Wei kingdom. In Chinese, *MU* means wooden, *MA* means horse, *NIU* means cow, therefore, after free translation *Mu Niu Lu Ma* means "a device powerful as horse and fast as cow." The *Mu Niu Lu Ma* walking machine, when pushed, transferred its legs in a sequence similar to that of a cow or a slowly moving horse. *Mu Nu Liu Ma* was used as a wheelbarrow for transportation of food supplies needed by the army. The machine was able to cover a distance of 10 km in a day in the rough terrain while carrying a load of 200–250 kg. However, no design details of *Mu Nu Liu Ma* are available [2]. This story of *Mu Nu Liu Ma* fascinated many researchers in China and Taiwan to reconstruct it in later times. The prototype reconstructed by Wan Jian from Xinjiang Institute of Technology (XX c) was the most famous one. His prototype was a very complex one consisting of ten links in each leg mechanisms resembling by view the horse or cow. The size and proportions of the mechanical components was chosen such that the leg-end trajectories were similar to the trajectories observed during walk of animals.

In the early ninth century the Khalif of Baghdad (786–833) took an initiative to retrieve the Greek texts that had been preserved by monasteries and scholars during the decline and fall of western civilization. He deputed three men, the Banu Musa, for this great mission. They compiled a great book *Kitab al-Hiyal* (The Book of Ingenious Devices) describing over hundred devices based on the works they collected while incorporating some additions of their own. The next significant work on automation was performed in the XII century AD by Badi'al-Zaman Isma'il ibn al-Razzaz al-Jazari. He compiled the text "The Science of Ingenious Mechanisms" consisting of various existing designs and some of his own inventions. He constructed a figure which upon manual emptying of a water basin automatically filled it again with water [8]. He also developed many other mechanical figures that were actuated by the force of gravity transferred by levers or hydraulics to move the limbs of figures.

The Arabs preserved, disseminated, researched, and applied the knowledge base of the Greek on the design and development of robotic mechanism during the age of decline and stagnation in the western civilization. This knowledge base later helped the scholars and genius like Leonardo da Vinci for the design and development of various mechanisms and robotic systems during the Renaissance of Europe [9]. It is interesting to note that the Arabs were interested to design and develop the mechanisms not only for creating dramatic illusion like Greeks but also for manipulating the environment for human comfort. Therefore, the greatest contribution of the Arabs was the idea of practical application of the earliest robotic science; this was the key element that was missing in Greek robotic science [8].

Leonardo da Vinci (1452–1519) was one of the great talents throughout the ages who performed much research and development works on robotics in a systematic manner with scientific outlook. The Renaissance revived the interest in the ancient

Greek art and science and at the same time also promoted the aspiration to verify, reconstruct, and improve upon the ancient achievements. Inspired by the spirit of Renaissance as well as Hero's works through the translated Arab texts, Leonardo actively engaged himself in verifying Greek reconstructions. A strong craftsmanship background acquired in his childhood apprenticeship in drawing, painting, sculpture, and architecture at Andrea del Verrocchio's workshop, as well as self-taught engineering and anatomy knowledge, provided Leonardo with the skills necessary to start where the ancient Greeks had ended [3]. His knowledge in anatomy and skill in drafting, metal working, tool making, armor design, and sculpture enabled him to build robotic mechanisms and machines. He used spring mechanisms as actuators in his ingenious machines [2]. Between 1495 and 1497 he designed and possibly built the first articulated anthropomorphic robot in the history of western civilization [3, 8, 10]. This armored knight, externally appeared as a typical German-Italian suit of armor of the late fifteenth century, was designed to sit up, wave its arms, and move its head via a flexible neck while opening and closing its anatomically perfect jaw. It was made of wood with parts of leather and brass or bronze and was cable operated.

In the XVI and XVII c., as the precision mechanics capabilities improved, dolls dancing and/or playing diverse musical instruments were designed by many watchmakers [2]. As we move through the ages toward the more recent time, examples of toys or machines with manipulation or locomotion abilities become more abundant. An excellent example of mechanical dolls was the mechanisms built in the XVIII c. by Swiss watchmakers Pierre Jaquet-Droz, Jean Frederic Leschat, Henri Jaquet-Droz, and Henri Millardet. Those dolls were programmable by exchange of pegs pushing cams. The dolls were capable of drawing and writing. As they were programmed, what was written or drawn could be changed. Very complex gears, cams, and levers inside their bodies were powered by spring mechanisms. Droz brothers miniaturized the mechanical components. In their dolls they often applied mechanism transferring the motion by chains and teeth wheels. Until now this mechanism in large size was used in milling machines, steam engines, and wall clocks.

In the eighteenth century, skilled craftsmen from the clock and watchmaking industry of Switzerland were hired, and the base technology of precision mechanical devices available in Switzerland was also adopted to build mechanical puppets in Europe [3]. These were basically entertainment devices and were programmable through stacked cams for achieving sophisticated movements. A mechanical duck was built by Jacques de Vaucanson and displayed throughout Europe in 1738. It was driven by multiple cams with one wing containing over 400 parts and was capable of eating, drinking, quacking, splashing its water, and even defecating. Excellent mechanical dolls were created by Swiss watchmakers Pierre Jaquet-Droz (1721–1790), Jean Frederic Leschat, Henri Jaquet- Droz, and Henri Millardet [2, 8]. Those dolls could write and draw figures and were programmable by exchange of pegs pushing cams. Very complex gears, cams, chains and teeth wheels, and levers inside their bodies were powered by spring mechanisms.

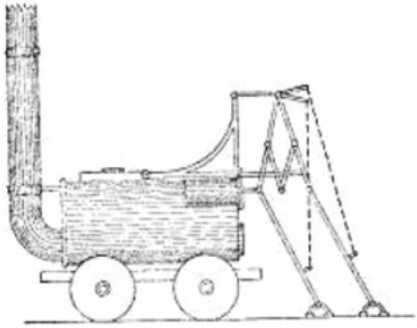


Fig. 2.1 Sketch of one of the first steam engine vehicles with legs [2]

From the XVII till the XIX century, legs were used as prerequisite for propulsion. An excellent example of a vehicle supported by wheels, but powered by legs, is the so-called Blueprint vehicle in XVIIIc. [2]. In the early steam engine vehicles, it was difficult to initiate and stop the motion of the vehicle due to low friction between the wheels and rails. Therefore, legs were added to stop and push the steam engine vehicles running over the rails [2, 3] (Fig. 2.1).

In 1850, the Russian mathematician Chebyshev presented a model for a locomotion system. It used a kinematic linkage to move the body along a straight horizontal path while the feet moved up and down to exchange support during stepping [3, 11]. People at that time viewed the task of building walking machines as the task of designing linkages that would generate suitable stepping motions when driven by a source of power [11].

Eadweard Muybridge was the pioneer in the study of animal locomotion on a scientific setting. He studied the different gaits of horses from the still photographs of trotting horses [3, 11, 12]. The results of this work were published on the Scientific American journal in 1878. After this initial study, Muybridge also studied and documented the gaits of 40 other mammals, including the gaits of human. His research and photographic data are still quite valuable resource for the modern robotics research and survived as a landmark in locomotion research.

L. A. Rygg in 1893 proposed the first quadruped machine, named "The Mechanical Horse" [3, 13] (Fig. 2.2).*The Mechanical Horse* was patented on 14 February 1893. In the design the stirrups were used as pedals so that the rider could power the mechanisms. The movement from the pedals was transmitted to the legs through gears that would result the stepping motions. However, there is no evidence to prove that he actually built this machine.

The Steam Man, a biped machine, was proposed by Georges Moore in 1893. Perhaps it is the earliest successful biped [3] (Fig. 2.3). It was powered by a 0.5 hp gas-fired boiler and reached a speed of 14 km/h. Stability was aided by a swing arm that guided him in circles. Traction was aided by heel spurs, smoke flowed from his head and steam from the nose, and a pressure gauge was conveniently mounted in his neck [8].

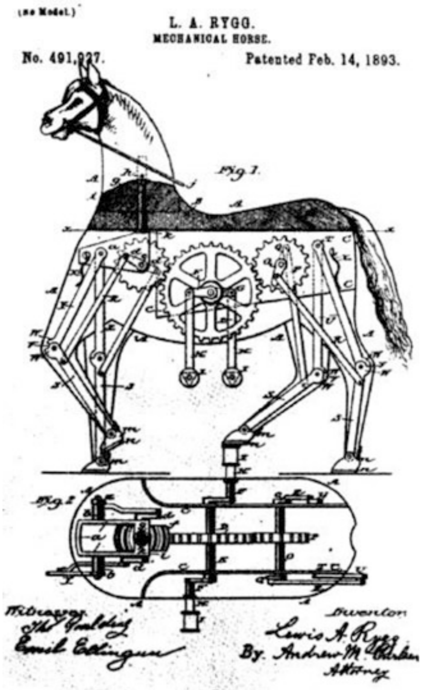


Fig. 2.2 Sketch of one of the first quadruped machines: *The mechanical horse* [3, 13]

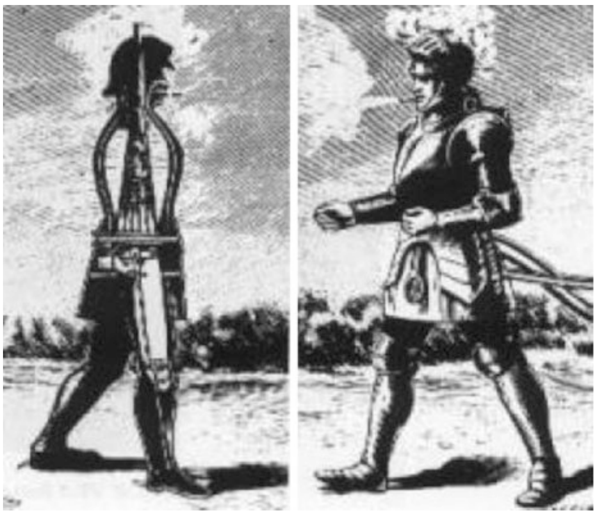


Fig. 2.3 The first biped machine: *Steam man* [3]

In 1913 the Bechtolsheim Baron patented a quadruped machine, shown in Fig. 2.4. There is no concrete evidence whether this machine was actually built [3, 13].

Although it is not quite apparent that which of the previously mentioned devices should be considered the first robot, the origin of the term “robot” is well known.

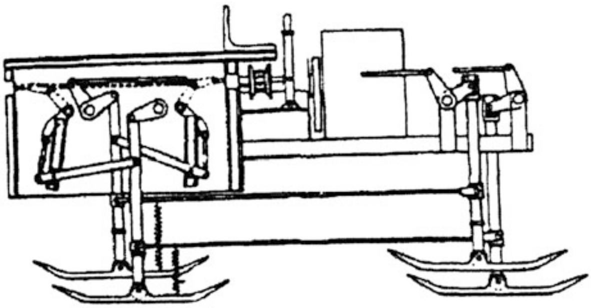


Fig. 2.4 Bechtolsheim baron's quadruped machine [3]

Karel Capek, a Czechoslovakian playwright, introduced the term "robot" from the Czech word "robota" meaning slave work, in a play called R.U.R. (Rossum's Universal Robots) in 1921 [14]. R.U.R. was a play about humanlike servants that were artificially created out of biological tissues to serve humans in factories and in the army. Capek called these artificial workers as "robots" [3, 7].

Later on in 1940, the idea of what is a robot and what are its capabilities was influenced by science fiction, mainly due to Isaac Asimov [3]. Isaac Asimov produced a series of short stories about robots for Super Science Stories magazine. Over the next 10 years he produced more stories about robots that were eventually recompiled into the volume "I, Robot" in 1950. Asimov is generally credited with the popularization of the term "Robotics" which was first mentioned in his story "Runaround" in 1942. But probably Isaac Asimov's most important contribution to the history of the robot is the foundation of his Three Laws of Robotics [7, 14]:

Law 1: A robot may not injure a human being, or, through inaction, allow a human being to come to harm.

Law 2: A robot must obey the orders given to it by human beings except where such orders would conflict with the First Law.

Law 3: A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Asimov later adds a "zeroth law" to the list:

Zeroth law: A robot may not injure humanity, or, through inaction, allow humanity to come to harm.

From the foregoing discussion it is clear that various novel ideas related to artificial walking mechanisms emerged from the ancient times till the nineteenth century. Although the development of mechanisms dominated in most of the cases, other aspects of walking machines like actuation, sensing, and control got very little attention from the developers due to the technological bottleneck prevailing at the contemporary period. Nevertheless these inventions were great inspirations for the next generation robotics engineers for the design and development of more advanced and more sophisticated autonomous walking machines to perform the intended tasks. XX c. was marked by an extensive development of diverse walking machines, and the history of walking machines after the Second World War is very rich and will be described in the next section.

2.2.2 Evolution of Modern Walking Robots

Like many other branch of science and engineering, walking robotics research also gathered a new momentum after the Second World War due to the new inventions in mechanisms, material science, electronics, control system, and computers. This laid the foundation of modern walking robotics research for the systematic design and development of walking machines for their intended applications in rough terrain. A number of research groups started to study and develop walking machines in a systematic manner from the mid-1950s. It took another decade to successfully design and build modern walking machines [13, 15].

In 1960, an extensive research of linkage mechanisms for legged locomotion was performed by Shigley [3, 12]. He proposed several leg mechanisms based on four-bar linkages, cam linkages, pantograph mechanisms, etc. for walking machines. He also built a vehicle with four rectangular frames where each frame was nearly as long as the body and served as a leg. The legs were controlled by a set of double-rocker linkages and they had to move in pairs, and the stroke was quite short to ensure static stability. Although it worked, but it required noncircular gears for uniform velocity of foot motion and was found as impractical [3, 12, 13]

In the early 1960s, Space General Corporation developed one six-legged externally powered and another eight-legged with self-contained power source walking machines for their application as lunar rover with legged locomotion [3, 13].The leg motions of both machines were coordinated by cams and transmitted by linkages. However, their terrain adaptability was poor due to lack of the necessary degrees of freedom.

Ralph Mosher of General Electric's General Engineering Laboratory started developing a four-legged walking truck, also known as the "General Electric quadruped" (Fig. 2.5), in the mid-1960s and finished the project in 1968 [3, 16]. This vehicle has three degrees of freedom (DOF) per leg—one in the knee and two in the hip. Each DOF was actuated through a crank by a linear hydraulic cylinder [13]. This vehicle, with 3.3 m height, 3 m long and 1,400 kg weight, was propelled by a 68 kW internal combustion engine. The machine control was dependent on a well-trained operator in order to function properly. The operator controlled the four legs through four joysticks and pedals that were hydraulically connected to the robot legs, with force reflection [3]. Controlling 12 DOF by human as a "supervisory controller" in the control loop was quite demanding. For this reason few people were able to operate it, and they also used to get tired after some time. However, this invention is very important in the history of modern walking robots because it demonstrated a walking machine capable to surpass obstacles and with good mobility in difficult terrains with versatile gaits. Nevertheless, it became clear that it was needed a computer control system for the coordination and control of the sequence of actuation of the leg joints.

The breakthrough development in the history of walking robots came in 1966, when a four-legged walking machine known as the "Phony Pony" (Fig. 2.6) was built by McGhee and Frank at the University of Southern California. This was the

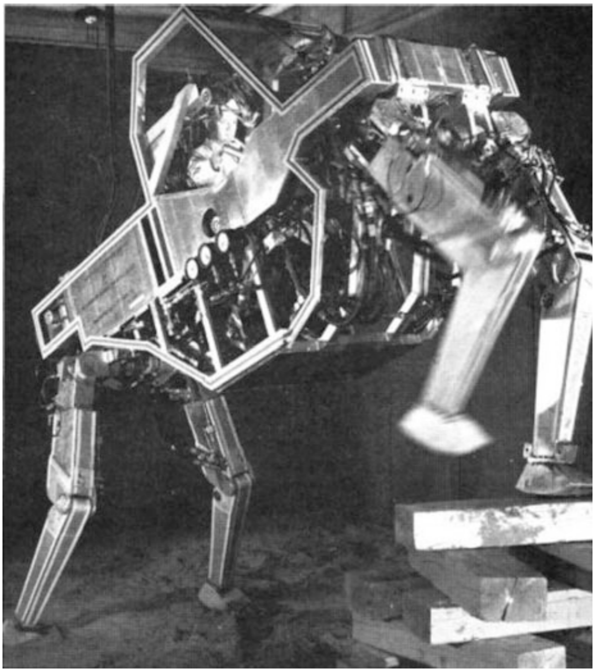
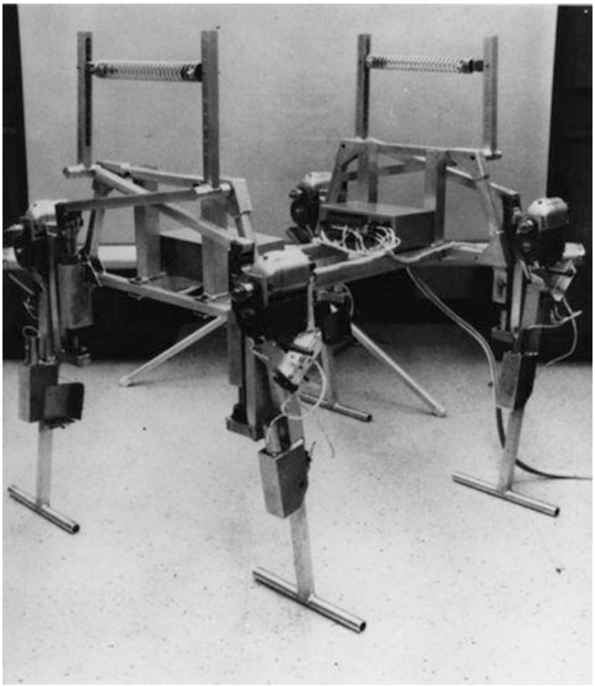


Fig. 2.5 General electric quadruped [3, 11]

first walking vehicle to walk under full computer control [13]. Phony Pony had two DOF in each leg, and the joint coordination was performed by the contemporary "digital computer" instead of cams of linkages. The leg mechanism had two links and two joints. Both joints were actuated by electric motors through a worm gear speed reduction system. The machine was powered externally through a cable. Phony Pony could walk with two different gaits: *the quadruped walk* and *the quadruped trot*. This was the big limitation of this walking machine that it could only walk in a straight line and not able to turn.

The research on biped locomotion, when compared with the multi-legged case, has advanced more slowly due to the difficulty in establishing a stable locomotion because biped robots are more demanding for their dynamic balance. However, development in robots with two legs occurred in much the same way as those with more legs [17]. Since the end of the 1960s, researchers at the Waseda University in Japan have developed a series of computer-controlled biped systems. In 1969, Ichiro Kato developed the biped robot WAP-1 at the Humanoid Research Laboratory. For its actuation, this robot had artificial rubber muscles, pneumatically actuated, and the biped locomotion was achieved through the playback of previously taught movements. Early bipeds had to be connected to large computational devices. WAP-1 used computers to alter artificial muscles connected to a twin-legged frame. The main initial limitation of this machine was its low speed, needing 90 seconds in order to complete a step. Latter advancements allowed reaching speeds near those achieved by human beings. Wap-2 and Wap-3 were

Fig. 2.6 Phony pony: The first computer-controlled walking robot [3]



developed in 1970 and 1971, respectively. Wap-3 was able to move its center of gravity on the frontal plane so that it was able to walk not only on a flat surface, but it could also descend and ascend a staircase or slope and turn while walking. The three-dimensional walking and turning that Wap-3 achieved were the first in the world. It was directed by a controller-based memory. Kato went on to develop numerous other biped machines and is regarded as a one of the main pioneers in the biped robotics research. In 1973, Kato constructed a humanlike robot known as Wabot-I. It was the first full-scale anthropomorphic robot in the world and was highly sophisticated. It had a limb control system, a vision system, and a conversation system. It was estimated that it had the mental ability of a one-and-a-half-year-old child [17]. Kato developed a variety of robots in the 1980s and applied 16-bit microcomputer to design versatile control system for the bipeds. He also built biped robot for the first time in the world that could perform quasi-dynamic walking. In 1985 Kato and his group developed a new robot that could descend stairs and slight inclines. This is far harder to do with a biped than quadrupeds because of the decreased stability and complex balance issues. In 1989 Kato and his group developed a walking control method (implemented in the WL-12RIII) which enables stable walking under unknown external forces and moments by using "cooperation motion of a trunk and lower limbs." This enabled increased speed of movement whilst ascending or descending stairs because of the added stability that this new system provided.

Fig. 2.7 The *big muskie* [3]

In 1969, Bucyrus-Erie Co. developed the *Big Muskie* (Fig. 2.7) for use in an open-air coal mine. It is perhaps the biggest off-road walking machine built so far and weighing around 15,000 ton. This machine had four hydraulically actuated legs. When it moved, the four legs raised the body and moved forward or backward one stride and then lowered the body on the ground. While the body remained on the ground, the legs lifted and moved to the next position. This motion was cycled by an electronic sequencer [3, 13].

In 1972, a group at the Institute Mihailo Pupin in Belgrade, Yugoslavia, built a pneumatically actuated biped exoskeleton to help paraplegics. It was controlled by analog computer [13].

In 1972, a six-legged walking machine was built by Petternella and his associates at the University of Rome [13]. It was actuated by electric motors and was similar to the Phony Pony in its control structure. They also attempted to establish interaction between the human operator and the walking machine.

Since 1972, Professor Kato at Waseda University, Japan, developed a series of computer-controlled bipeds [13]. These biped walking machines could operate at a very slow speed and could climb stairs under the control of an operator.

In 1974, a six-legged vehicle was built at Moscow Physico-Technical 1nstitute in Russia. Subsequently in 1978, Okhotsimski and his colleagues described about the development of two six-legged walking machines [13]. One of these six-legged walking machines was controlled by analog computer and the other one was equipped with a scanning distance-measuring system. Both the machines were powered externally, and one of them could turn in its body length. The machines had insect-type legs with three DOF with one upper link and one lower link. The joints were actuated by motors and gears, and foot pad was attached on the lower link with a gimbal joint.

Fig. 2.8 The OSU hexapod [18]

In 1977, the OSU Hexapod was built by McGhee and his associates at the Ohio State University to study control algorithms for a walking machine [18] (Fig. 2.8). It was a six-legged walking machine and weighing about 300 pounds. It was fully controlled by a PDP 11/70 computer via an umbilical cable and was powered externally through a cable. Each leg of this vehicle had three DOFs and consisting of two links connected by joints, and each joint was actuated by an electric motor through a worm gear. The walking vehicle was later equipped with force sensors, gyroscopes, proximity sensors, and a camera system.

Matsuoka was the pioneer to develop a monopod walking robot, which performed locomotion through hops, with an objective to model the cyclic jumps in human locomotion in 1979 [3]. He formulated a model, consisting of a body and a weightless leg (to simplify the problem), and considered that the support phase duration was short when compared with the ballistic flightphase in which the feet lose contact with the ground. This gait, in which almost the entire cycle is spent on the transfer phase, minimizes the inclination influence during the support phase. His one-legged hopping machine could stand over an inclined table (10° with the horizontal), and an electrical solenoid gave a fast impulse to the foot in such a way that the support period was small. The machine hopped in place with a period of one hop per second and could walk forward and backward over the table.

Hirose and Umetani in 1980 built PV-II shown in Fig. 2.9, a four-legged walking machine, at Tokyo Institute of Technology, Japan [13]. Its weight was only 22 pounds and could walk at a very slow speed of the order of 0.8 inch per second. Its power consumption was very small of the order of only 10 W due to its small weight, sophisticated leg design, and slow average speed of locomotion. The leg

Fig. 2.9 PV-II walking robot [19, 20]

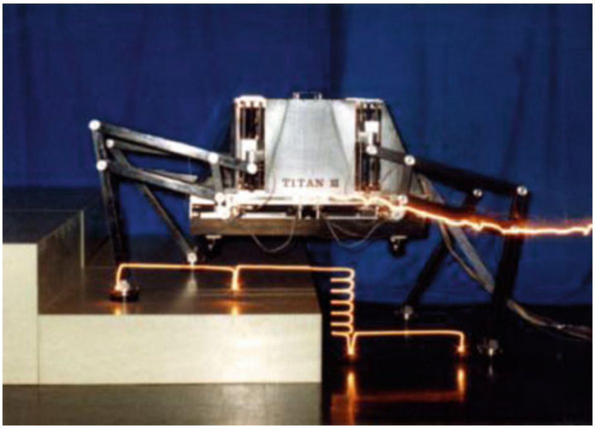


Fig. 2.10 TITAN-III [19, 20]

mechanism was a three-dimensional pantograph type, and the leg actuation was accomplished by DC motors and power screw speed reduction system. In addition, a passive ankle system was also included in the leg mechanism. PV-II was powered from external electrical energy source, and the control signals were also applied to it from an external computer via an umbilical cable. Its control system enabled it to maintain a horizontal body orientation. Contact sensors on each foot were used to detect obstacles in its path and contact with the ground. Later in 1984, an enlarged version of PV-II was built by them and named as TITAN-III (*T*okyo *I*nstitute of *T*echnology, *A*ruku *N*orimono (walking vehicle)) [19, 20]. The total weight of TITAN-III shown in Fig. 2.10 was 176 pounds and had four legs of about 4 ft long. The leg mechanism was of three-dimensional pantograph type and was built from composite materials. The latest walking robot in the TITAN series is the TITAN-XI built in 2008, a 7,000 kg hydraulic quadruped robot developed as a construction machine for drilling holes to reinforce steep slopes with rock or anchor bolts and thus preventing landslide. Its leg length is 3.7 m.

Vohnout at the Ohio State University built a one-legged walking machine, the Monopod, in 1982. It was a 20-inch high four-bar leg and was mounted on the inner frame of a three-wheeled cart. The inner frame was free to move vertically relative to the cart. The leg pushed the cart forward during the contact phase of its walking. The machine was controlled externally by a PDP 11/70 computer which was later replaced by an onboard Intel 8086 microprocessor-based microcomputer. The Monopod was built to test the energy efficiency of the four-bar leg. The tested data was compared to the data of the OSU Hexapod, and an improvement in specific resistance by a factor of 20 was obtained [13].

In 1982, a six-legged passive walking machine, the DUWE, was built by Brown at the Ohio State University [13]. The DUWE could walk in alternating tripod gait synchronizing each of the three legs by a pulley and wire system. The vehicle was controlled by an Apple II microcomputer. Although the leg structure was similar to that of the Monopod, the foot was lifted by shortening the driven crank via a toggle mechanism actuated by a solenoid.

The first self-contained walking machine was built by Sutherland in 1983 [13]. It was a hydraulically actuated six-legged vehicle and controlled by an onboard microcomputer. A gasoline engine was installed on board to give electric power supply to the computer as well as to drive a set of hydraulic pumps. Each leg of the machine had three DOF it could walk on smooth terrain and carry a human operator.

Odetics Inc. developed a six-legged “Functionoid” the ODEX-I in 1983 [13]. The weight of ODEX-I was only 370 pounds; however, it could lift up to 900 pound weight. This machine was powered by an onboard aircraft battery and was controlled by onboard computers that used to receive commands from a joystick via radio telemetry. The six legs, each with three DOF and designed as a planar modified pantograph mechanism, were mounted around the body.

Raibert at Carnegie-Mellon University built a hopping machine in 1983 [3, 13]. This hopping machine had only one leg and body structure that contained the actuators and several sensors to measure the body inclination angle, the hip angle, the leg width, the spring leg stiffness, and the ground contact. This machine was powered and controlled externally. This first prototype was limited to operate on a level surface and, therefore, could only move up and down, front and back, or rotate in the plane. A second hopping machine prototype, named Pogostick, had an additional hip joint to allow the leg to move sideways, as well as forward and backward. During operation, this robot balanced itself while hopping, moving at a maximum speed of 2.2 m/s.

Adaptive suspension vehicle (ASV), a very popular hydraulically actuated hexapod robotic platform with capability to adapt very rough terrain during locomotion, was developed at the Ohio State University, together with the University of Wisconsin and the Environmental Research Institute of Michigan, at the end of 1985 [3, 13, 18]. ASV had a total weight of 2,720 kg with 250 kg payload capacity. It was 5.6 m long and was powered by an internal combustion engine. The maneuvering and vehicle state supervision tasks were performed by an operator. The operator used to control the vehicle locomotion speed and direction through a joystick, but the individual control of each leg was performed by a central computer. The ASV also had optical radar to study the terrain in front of it and to decide on the front foot placement. It could negotiate a maximum slope of 60 %, cross 1.8 m width ditches, climb vertical steps with 1.65 m maximum height, cross isolated walls of 1.35 m height, and reach a maximum speed of 2.3 m/s over regular terrain.

The project of developing a biped robot, known as the Honda Humanoid Robot, began in 1986, and the key ideas adopted for its development were "intelligence" and "mobility," since the robot should coexist and cooperate with human beings [3, 21]. The development of the Honda Humanoid Robot was based on data retrieved from human locomotion. Honda's idea was to create a robot that could be used in daily life, in contrast to a robot developed for a particular application, aiming its introduction in factories. Honda also specified three functions that had to be fulfilled: the locomotion speed should correspond to that of a human being (approximately 3 km/h), the robot structure should be capable of supporting arms with hands, and should be able to climb up and down stairs. The more advanced version of this robot, known as ASIMO (Advanced Step in Innovative MObility) model, was built in 2000, having 1.2 m height and 43 kg weight. The ASIMO has 26 DOF, is electrically actuated, and can hold 0.5 kg in each hand. It was a completely autonomous robot, in terms of processing capability and in terms of power (it transports on its back batteries that allow 15 min autonomy). It was intended to perform people attendance tasks and museum visit guiding, due to the integration of a vision and audition sensors set and a human gesture recognition system, allowing this humanoid to interact with human beings.

A hexapod robot named Genghis was built at MIT in 1989. Genghis was famous for being made quickly and cheaply due to construction methods. Genghis was a small six-legged robot that could walk, climb over obstacles, and follow people. It used four microprocessors, 22 sensors, and 12 servo motors. Rodney Brooks took the idea of a finite state machine and used it to build layered levels of behavior on Genghis.

Professor A. Halme at the Helsinki University of Technology, Finland, developed a hydraulically actuated six-legged walking machine, known as MECHANT (MECHanical ANT) in 1992 [22]. Its weight was about 1,100 kg and was driven by a 38 kW 2-cylinder ultra-light aero plane engines with air cooling. The hydraulic system was a traditional one including valve-controlled system with central pump, the work pressure being about 300 bars. The body was constructed of rectangular aluminum tubes which are welded together, forming a rigid structure. The leg mechanism was a two-dimensional pantograph with vertical rotation axis, thus having three DOF. The operator controlled the vehicle remotely by the joysticks via the radio link. The control system of MECHANT consisted of a computer network connecting seven onboard computers running under a commercial real-time operating system.

Another successful field robot, named DANTE, was developed by the CMU Field Robotics Center in 1993. DANTE was an eight-legged walking robot developed for the mission to collect data from a harsh environment such as those found on planetary surfaces. It descended into Mt. Erebrus, Antarctica. The mission failed when, after a short 20-foot decent, DANTE's tether snapped and it dropped into the crater. Later in 1994, DANTE-II was built. It was a more robust version of its predecessor and successfully descended into the crater of Alaskan volcano Mt. Spurr in order to gather and analyze high-temperature gases from the crater ground. DANTE-II was also an eight-legged robot and was electrically actuated. The power was supplied externally through an umbilical cable that also served as a communication structure and rescue cable. Besides contributing to volcano exploration advancement, another primary objective of this robot is to show the possibility of robotic exploration of extreme environments.

In 1997, a planar one-legged walking machine, known as ARL Monopod-I, was built by the Ambulatory Robotics Lab (ARL) at Canada. This planar monopod was inspired from the work of Raibert and was electrically actuated. It could attain a top running speed of 4.3 km/h. It was quite energy efficient and consumed only 125 W of electrical power. An improved version of ARL-I was built, known as ARL-II monopod, in 1999. ARL-II could attain a maximum running speed of 4.5 km/h with a total mechanical power expenditure of only 48 W. The ARL Monopod-II employed an electrical motor to actuate a lead screw, as well as a storage/recovery energy system through springs [3].

The design of the configuration of hopping machines' legs has been done as an approximation of the animal's legs. Moreover, many monopod robots that use the hopping principle for their locomotion also have feet with special geometry to maintain balance when stopped [3]. These robots allow jumping over obstacles or positioning themselves in places where available places for feet placement exist, without worrying about the static stability. In this connection it can be mentioned that in 1945, Wallace patented a "hopping" tank that could move on with one leg. During motion, it would lead to an erratic trajectory and, therefore, would be difficult to be shot by the enemy. Another potential application for these robots is the exploration of small celestial bodies like satellites, asteroids, comet nucleus, where legged or wheeled robots are not able to move successfully due to the reduced local gravity. An actual example is the vehicle ПРОП-Ф (Hopper), designed by the Russian Mobile Vehicle Engineering Institute, and sent in a space mission to Phobos in 1998. This 45-kg robot was able to move using hops, perform scientific experiments and transmit the collected data and the experimental results to the Earth through a radio communication channel.

The WABIAN (WAseda BIpedal humANoid) biped robot is another example of a biped robot that has been developed in Japan in 1997. The main objective of this robot development was the creation of an anthropomorphic robot sharing the same work space and presenting thought and behavior patterns similar to those of the human being. It was intended to achieve a robot able to interact in a natural way with humans, namely, being able to talk and to present emotions [3]. This biped robot, with 43 DOF, 136 kg weight, and 1.97 m height, was electrically actuated. The head had the capability to gather visual information (through a stereo artificial vision system) and audition. The electrical power was externally supplied; however, all the processing and computing system was integrated on the robot itself. To further increase the similarity with human beings, on this robot the hip joints were antagonistically actuated and with variable stiffness, in a similar way to the human joint actuation (each human joint is actuated by two or more muscle groups that present characteristics identical to nonlinear springs). In terms of locomotion capabilities, this robot was able to move forth and back, dance in a dynamic way waving its arms and hips and to transport some load, using its arms.

A huge advancement has been made in the research on biped locomotion during the last decade in Japan partially due to the implementation of the HRP-Humanoid Robotics Program supported by the METI—Ministry of Economy, Trade and Industry of Japan between 1998 and 2002. The main objective of this program was similar to that followed in the development of the biped WABIAN. One example of a biped robot that has been developed under this program is the HRP-2 humanoid (Humanoid Research Project) [3]. This robot is able to move on irregular surfaces at 2/3rd of the normal human speed and is able to cross narrow passages, modifying its gait for that purpose. If the robot loses balance and falls, besides the fall being controlled in order to minimize eventual damage to the structure, it is capable of rising alone.

In 1999, Sony designed and manufactured a four-legged robotic pet, known as the AIBO (*A*rtificial *I*ntelligence ro*BO*t, also means "love" or "attachment" in Japanese, can also mean "partner"). The AIBO was an inexpensive platform for artificial intelligence research, because it integrated a computer, vision system, and articulators in a package vastly cheaper than conventional research robots.

A hexapod Walking Harvester was developed by Plustech Oy Ltd (presently John Deere Forestry Oy) in 2000 for forestry work. This vehicle has three hydraulically actuated DOF on each leg and is fed from a diesel engine, allowing it to reach aimed maximum speed. For maneuvering, it needs a human operator who controls the machine through a joystick.

The SILO4 [23] walking robot is a medium-sized quadruped mechanism built at Instituto de Automatica Industrial, Spain, for basic research and development as well as an educational robot in 1999 and tested till 2003. The body of the SILO4 is a parallelepiped of about 310 mm $\times$ 300 mm $\times$ 300 mm. It contains all the drivers and electronic cards, as well as the force sensor amplifiers and a two-axis inclinometer that provides pitch and roll body angles. The structure of the body is made of aluminum, and the body's weight, including electronics, is about 18 kg.

SCOUT-II has been designed and constructed at Ambulatory Robotics Laboratory, McGill University, Canada, in 2000. It is an under-actuated walking robot; therefore, its control is quite challenging. SCOUT-II is fully autonomous having on board power, computing, and sensing. Other features include an on board pan-tilt camera system and laser sensors.

BigDog is a dynamically stable quadruped robot created in 2005 by Boston Dynamics with Foster-Miller and funded by DARPA. It is 3 ft (0.91 m) long, 2.5 ft (0.76 m) tall, and weighs 240 pounds (110 kg), about the size of a small mule. It is capable of traversing difficult terrain, running at 4 mile/h (6.4 km/h), carrying 340 pounds (150 kg), and climbing a 35-degree incline. Locomotion is controlled by an onboard computer that receives input from the robot's various sensors. Navigation and balance are also managed by the control system.

Professor Kenzo Nonami and his group at Chiba University, Japan, have worked for more than the last on decade for development of six-legged land mine detection and removal robot for *humanitarian demining* [24, 25]. They developed a series of robots called COMET (*C*hiba university *O*perating *M*ine detection *E*lectronics *T*ools). In this series COMET-I, COMET-II, COMET-III, and COMET-IV have already been developed and successfully tested in various terrain conditions with various robust and intelligent control algorithms for its effectiveness in locomotion. COMET-I and II are electrical motor actuated, whereas COMET-III and COMET-IV are hydraulically actuated. The mass of COMET-I is about 120 kg, length of the body is 80 cm, width of the body is 120 cm, and the height is 80 cm. COMET-I has exhibited interesting results during locomotion in various terrains and motivated to develop a more advanced version after COMET-II after solving the drawbacks of COMET-I. COMET-II has a speed of locomotion of about 150 m/h which is ten times faster than COMET-I. Its mass is about 100 kg. In order to provide sufficient power to walk on uneven terrain with heavier payload (of the mine detection and removal tools), COMET-III has been hydraulically powered. Its weight is about 900 kg, 4 m long, 2.5 m wide, and 0.8 m high. Its prime mover is a 700 cc gasoline engine, and the driving force of the hydraulic system is 14 MPa.

2.3 Modern and Future Perspective of Walking Robot Research

The robot has to interact with the environment with one or more effectors that are suitable to perform the intended task. They are very important element of any robotic system, and their nature, capability, and mode of utilization give an identity and distinctiveness. In autonomous robotic systems, there are two basic ways of using effectors so that the point of action of the effector falls within the robot workspace: (1) to move the robot around (which results "locomotion") and (2) to move other object around (which results "manipulation"). These actually divide present day robotics into two separate categories: (1) mobile robotics and (2) manipulator robotics. Many kinds of effectors and actuators can be used to move a robot around, like legs (for walking/crawling/climbing/jumping/hopping), wheels (for rolling), arms (for swinging/crawling/climbing), and flippers (for swimming). While most animals use legs to get around, legged locomotion is a very difficult robotic control problem, especially when compared to wheeled locomotion.

The main challenges [9, 19] those are still present for the development of autonomous walking robot are: (1) nonavailability of energy-efficient and high-performance actuators with high torque to weight ratio and high torque to volume ratio; (2) reliable and economical sensors; (3) lightweight but mechanically strong material for construction of the structure and mechanism; (4) fast, high computing power, and economical dedicated computer system that must be suitable for any type of hostile situation of nature; and (5) lightweight and onboard power source for long duration energy autonomy.

Another significant aspect of modern walking robotics research is the development of biologically inspired design that involves the idea of transferring the biological principles of nature to the robotic systems [26–34]. It has been observed that a large variety of efficient mechanical and physiological designs have evolved in nature in order to fit with the characteristics of a given physical environment and different locomotion modes. Animals seem to have evolved to be as fast as possible; to have the best possible acceleration, maneuverability, and endurance; and to have energy consumption as low as possible [1]. At a first glance, one may get tempted to mimic a legged animal while designing a walking robot. However, it is not possible to completely mimic a living system because the principle of energy supply, actuation, sensing, control, and intelligence of a biological system is entirely different from the artificial energy supply, actuation, sensing, control, and intelligence. Therefore, from engineering perspective the main focus of biologically inspired robotics is not to create a new generation of robots that imitate life but to use principles from nature to improve robotic systems [29]. As the concepts of the biological world are very hard to transfer to the walking machines, mainly due to the bottleneck in mechatronics, in the recent past many laboratories and their researchers were involved in the design and development of artificial locomotion systems with suitable modification of the principles observed in the biological world to accommodate the existing mechatronic technology. Therefore, the mechanical structures of the legs still comprise of several links connected by prismatic or rotational joints, with the proportion of the links or the location of the joints resemble to the living creatures [21]. Off course few attempts have been made to optimize the geometry of the leg mechanisms to match with the morphology and performance of living legged systems. However, due to the complexity of design and fabrication, the progress so far is very little [19, 35]. This is a future area of research where the robotics researchers should pay attention and many advanced technologies, like nanotechnology, micro electromechanical systems, single-chip computer, and smart materials, may help mankind to develop a walking robot that will resemble to the living legged systems.

Ever since, developments have mainly been driven to resemble physical aspects, although in the last few years, one of the main challenges in robotics has been to endow these machines with a grade of intelligence in order to allow them to extract information from the environment and use that knowledge to carry out their tasks safely. Although much progress has been made in the theoretical development of artificial intelligence, however, the applicability of most of the algorithms in real time is difficult or sometimes not feasible. The present trend to design intelligent robotic system is to impart prior knowledge with capability of learning in an integrated manner [9, 29, 35, 36]. Another important development in walking the robotics research during the last decade is the introduction of social behavior during the design of the control system. Therefore, the day is not very far when the walking robots will not only function as a machine but also blend themselves in our social environment and interact with people and play more important roles in our society [21].

The walking robotics research is still confined to the laboratory. The time is approaching when the commercial production of walking robot will start to commensurate with the future domestic, commercial, and industrial need. Obviously, like the industrial manipulator, this demand will have cumulative impact on further growth of the production of walking robot industry and reduce the cost of its production. Most of the innovations in the development of walking robots have occured, so far, in Japan [17].

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