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An Overview of Legged Robots

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Abstract *— The objective of this paper is to present the evolution and the state-of-the-art in the area of legged locomotion systems.*
In a first phase different possibilities for mobile robots are discussed, namely the case of artificial legged locomotion systems, while emphasizing their advantages and limitations. In a second phase an historical overview of the evolution of these systems is presented, bearing in mind several particular cases often considered as milestones on the technological and scientific progress. After this historical timeline, some of the present day systems are examined and their performance is analyzed. In a third phase are pointed out the major areas for research and development that are presently being followed in the construction of legged robots. Finally, some of the problems still unsolved, that remain defying robotics research, are also addressed.

1 Introduction

Autonomous robotic systems may be classified, generically, in two major areas:

- Manipulation robotics;
- Mobile robotics.

Regarding mobile robotics, and concerning the adopted locomotion strategy, there is the need to consider the following aspects of the problem:

- The requirements of the task that the robot must fulfil;
- The restrictions of the terrains in which the robot must operate;
- The limitations of the adopted actuators;
- The power source available to feed the robot and the required energy autonomy.

Bearing these ideas in mind, there are three fundamental configurations that may be adopted for mobile robots locomotion on ground:

- Rotational devices, such as wheels and tracks;
- Legs, similar to the ones observed on animals;
- Articulated structures similar to a snake's body.

Each of these locomotion configurations presents specific characteristics, which make them adequate for particular classes of applications.

2 Mobile Robotics

2.1 Wheeled and Tracked Vehicles

In the present state of civilization the locomotion using wheeled vehicles is dominant. Its use for performing the most various tasks is so common that one might think this to be the only available (or more effective) way of locomotion. However, through a detailed analysis of the characteristics of this type of locomotion, it is possible to conclude that things are quite different.

It should be noted that wheeled vehicles demand paved surfaces (or at least regular) in order to move, being extremely fast and effective in these surfaces. At the same time these mechanisms can be simple and have a light weight. However, more than 50% of the Earth surface is inaccessible to traditional vehicles (with wheels and tracks) (Anon, 1967) being difficult, or even impossible, that wheeled vehicles surpass large obstacles and surface unevenness. Even all-terrain vehicles can only surpass small obstacles and surface unevenness but at the cost of high energy consumption (Bekker, 1960).

An alternative consists on tracked vehicles. Although they present increased mobility in difficult terrains they are not able to surpass many of the found difficulties and its energy consumption is relatively high.

To these problems, one must add the fact that traditional vehicles leave continuous ruts on the ground, which in some situations is disadvantageous as, for instance, from the environmental point of view.

2.2 Legged Vehicles

2.2.1 Legged Vehicles Advantages

From what was seen, it is possible to conclude that legged locomotion vehicles present a superior mobility in natural terrains, since these vehicles may use discrete footholds for each foot, in opposition to wheeled vehicles, that need a continuous support surface. Therefore, these vehicles may move in irregular terrains, by varying their legs configuration in order to adapt themselves to surface irregularities and, on the other way, the feet may establish contact with the ground in selected points in accordance with the terrain conditions. For these reasons, legs are inherently adequate systems for locomotion in irregular ground. When the vehicles move in soft surfaces, as for instance in sandy soil, the ability to use discrete footholds in the ground can also improve the energy consumption, since they deform the terrain less than wheeled or tracked vehicles and, therefore, the energy needed to get out of the depressions is lower (Bekker, 1960; Bekker, 1969). Besides, the contact area among the foot and the ground can be made in such a way that the ground support pressure can be small. Moreover, the use of multiple degrees of freedom (dof) in the leg joints, allows legged vehicles to change their heading without slippage. It is also possible to vary the body height, introducing a damping and decoupling effect between terrain irregularities and the vehicle body (and as a consequence of its payload). In what concerns locomotion, it should also be mentioned the possibility that these systems present to hugging themselves to the terrain in which they move. This is particularly true, in case they move, for instance, over the outside surface of pipes, in order to increase their balance ability (Kaneko, *et al.*, 2002).

Another advantage that is recently being investigated, concerns failure tolerance during static stable locomotion. The consequence of a failure in one of the wheels of a wheeled vehicle is a severe lost of mobility, since all wheels of these kinds of vehicles should be in permanent contact with the ground during locomotion. However, legged vehicles may present a redundant number of legs and, therefore, can maintain static balance and continue its locomotion even with one or more of its legs damaged (Yang and Kim, 1998; Hirose and Kato, 1998; Lee and Hirose, 2000; Yang, 2003; Spenneberg, *et al*., 2004).

Last, it should be mentioned that legs can be used not only for locomotion purposes, but also with the vehicle immobilized. For instance, the body can be actively actuated while feet are fixed to the ground, working as an active support base for helping the motion of a manipulator (Nonami and Huang, 2001; Garcia, *et al*., 2003) or a tool (Ihme, 2003) mounted on the body. As an alternative to the assembly of a manipulator on the robot body, multilegged robots can use one or more of its legs to manipulate objects, as it is possible to see in some animals (several animals use their legs to hold, manipulate and transport objects).

As an example, Takita, *et al*. (2003) present a biped robot, whose structure is inspired in dinosaurs, on which the tail is used to help maintain balance during locomotion and during manipulation tasks, that the robot performs with its neck, is used so that the robot can stand on it, making a stable support tripod. Hirose and Kato (1998) propose using the TITAN-VIII quadruped robot in the task of land mines detection and removal. For this purpose it is used one of the robot legs, presenting the function of a manipulator arm, with the possibility of being equipped with a set of different end effectors. Omata, *et al*. (2002) also propose the adoption of a quadruped robot for manipulation tasks, on which two of its legs are used for locomotion, while the body and remaining legs are used for object manipulation. Takahashi, *et al*. (2000) and Koyachi, *et al*. (2002) present similar solutions to the previous ones, but for hexapod robots.

The presented solutions have as advantages the reduction in the system weight and the corresponding increase in energetic autonomy, because otherwise it would be needed to mount arms on the locomotion system devoted only to manipulations tasks.

2.2.2 Legged Vehicles Limitations

Although the referred aspects indicate that legged locomotion is advantageous when compared with traditional locomotion vehicles, it should be kept in mind that, in their present state of development, these vehicles still suffer from huge limitations, since they exhibit low speeds, are difficult to build and need complex control algorithms. Besides, today's mechanisms are heavy, since they need a large number of actuators to move multiple dof legs, to which one should add large energy consumption.

2.3 Articulated Body Vehicles

Articulated body robots are composed by several body segments, connect in such a way to imitate a snake (Hirose, 1993; Nilsson, 1998; Klaassen and Paap, 1999; Kyriakopoulos, *et al*., 1999; Worst, 1998; Paap, *et al*., 2000; Streich and Adria, 2004) or a centipede (Long, *et al*., 2002). Through the active coordination of the different segments movement, these vehicles present certain advantages:

- Are able to move along and cross irregular terrains and narrow passages, actively adapting its long body to the terrain profile;

- Are able to cross ditches, hardening the joint servomechanisms in order for them to form a bridge. They are also able to cross, on a stable basis, swamp terrains, by weakening the joint servomechanisms in order to distribute its weight over its all segments;
- Present high reliability and easy maintenance due to their redundant unified structure. The malfunction segment can be easily disconnected and separately repaired;
- Can be easily transported, dividing the robot in its elementary segments.

2.4 Application Fields

Mobile robots, independently of its locomotion principle, are adequate for 3-D environments (*Dirty*, *Doll*, *Dangerous*). These vehicles are able to replace human beings, in order to avoid endanger their lives, in all kinds of dangerous works that require heavy safety measures or in areas to which the humans can not easily access.

In the case of legged locomotion robots, examples of these situations are:

- Remote locations exploration:
    1. In volcanoes (Wettergreen, *et al*., 1993);
    2. In space or other planets (Bares, *et al*., 1989; Kemurdjian, *et al*., 1995; Preumont, *et al*., 1997; Fiorini, 2000; Kubota and Takahashi , 2003; Kennedy, *et al*., 2005a; Kennedy, *et al*., 2005b);
    3. In the sea bottom (Ayers, *et al*., 2000a; Ayers, *et al*., 2000b);
- Hostile or dangerous environments:
    1. In nuclear power plants or in places with high radiation levels (Konaka, 1991);
    2. In mining prospecting and exploration (Cox, 1970; Roberts, *et al*., 1999);
    3. In demining and unexploded munitions recovery tasks (DeBolt, *et al*., 1997; Hirose and Kato, 1998; Flannigan, *et al*., 1998; Ayers, *et al*., 2000b; Nonami and Huang, 2001; Marques, *et al*., 2002; Garcia, *et al*., 2003);
    4. In disaster areas or catastrophe situations (Konaka, 1991; Mae, *et al*., 2000; Kikuchi, *et al*., 2003);
    5. In search and rescue operations (Mae, *et al*., 2000);
    6. In military operations (Caldwell and Warren, 2001).

Besides these applications, legged vehicles can also be used in a large variety of tasks such as (Hirose, 1991; Tsukagoshi, *et al*., 1997):

- In excavation and construction works (Hasunuma, *et al*., 2003);
- In cutting and tree transport in forests;
- In helping humans during payload transport operations (Neuhaus and Kazerooni, 2000; Yokoyama, *et al*., 2003);
- In medical applications, such as colonoscopy (Kim, *et al*., 2002) and as an alternative to wheelchairs (Takeda, *et al*., 2001; Sugahara, *et al*., 2004);
- In services, especially for in building people support applications (Sakagami, *et al*., 2002; Nishiyama, *et al*., 2003).

In addition, some predictions point out to the introduction of these robots in homes, either devoted to domestic tasks (Sawasaki, *et al.*, 2003), or as simple companions.

Last, it should be mentioned the success that some legged locomotion robots have been presenting in the entertainment (Fujita, 2000; Kuroki, *et al.*, 2003) and even in the education areas (Kitano, *et al.*, 2000).

However, in the present state of development of these equipments, one can not state that they present and effective locomotion alternative to wheeled and tracked vehicles, since several engineering problems remains unsolved.

After this brief introduction to the possible different forms of locomotion in mobile robots, emphasizing artificial legged locomotion systems characteristics, in the following section an historical perspective of legged locomotion vehicles development will be presented, giving some particular examples usually considered as milestones on its evolution.

3 Legged Vehicles Evolution

Although it might seem that we are in face of a “new science”, the first concepts in the area of legged locomotion are already quite old.

3.1 First Ideas

The first ideas to implement legged locomotion vehicles date from the XV century. Between 1495 and 1497 Leonardo da Vinci designed and possibly built the first articulated anthropomorphic robot in the history of western civilization. This armoured knight was designed to sit up, wave its arms and move its head via a flexible neck while opening and closing its anatomically correct jaw. Leonardo’s robot outwardly appears as a typical German-Italian suit or armour of the late fifteenth century. It was made of wood with parts of leather and brass or bronze and was cable operated. The robot project was a significant outgrowth of Leonardo’s anatomical and kinesiology studies, forming a bridge between his mechanical works and his anatomical studies (Rosheim, 1997).

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 (Raibert, 1986).

Figure 1 shows a sketch of one of the first vehicles with legs, dated from the XVIII century. In this vehicle, based on a steam engine, the motion transmission isn’t made by the wheels but through a set of legs.

In Figure 1 it is possible to see a drawing of the first quadruped machine, named The Mechanical Horse, whose project is by L. A. Rygg. In this machine the stirrups double as pedals so the rider can power the stepping motions (its movement was transmitted to the legs through gears). The reins move the head and forelegs from side to side for steering. This machine was patented in February, 14, 1893, but there is no evidence to prove that he actually built this machine (Raibert, 1986).

Figure 2 presents the biped machine named The Steam Man. This machine, project by Georges Moore in 1893, was, perhaps, the earliest successful biped. It was powered by a 0.5 hp gas fired boiler and reached a speed of 14 kmh^{-1}. Stability was aided by a swing arm that guided him in circles. Traction was aided by heel spurs, smoke flowed from his head, steam from the nose and a pressure gauge was conveniently mounted in his neck (Rosheim, 1994).

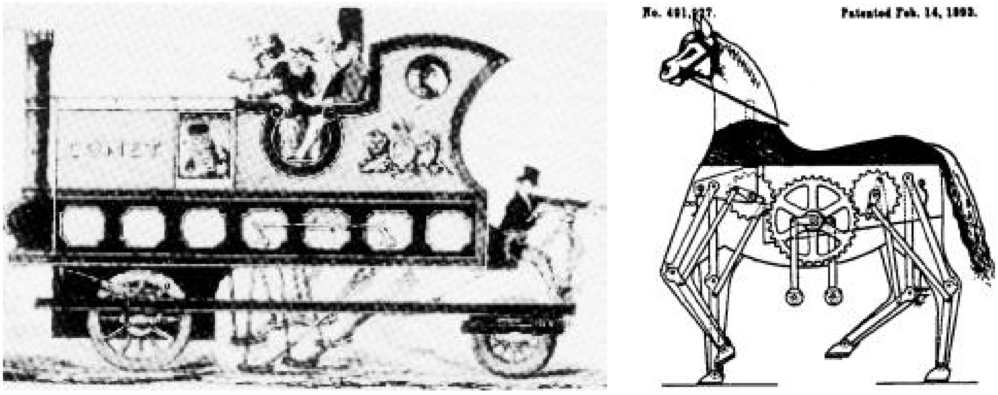

Figure 1: Sketches of one of the first legged vehicles (left) and of the first quadruped machine (right)

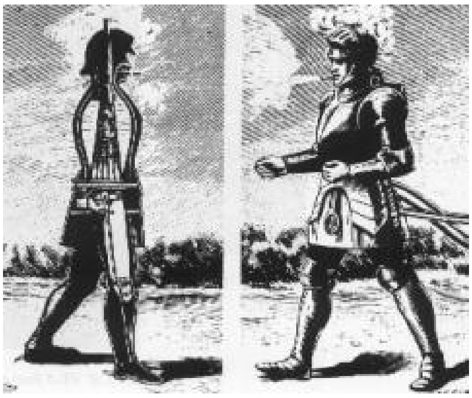

Figure 2: Project of the first biped machine

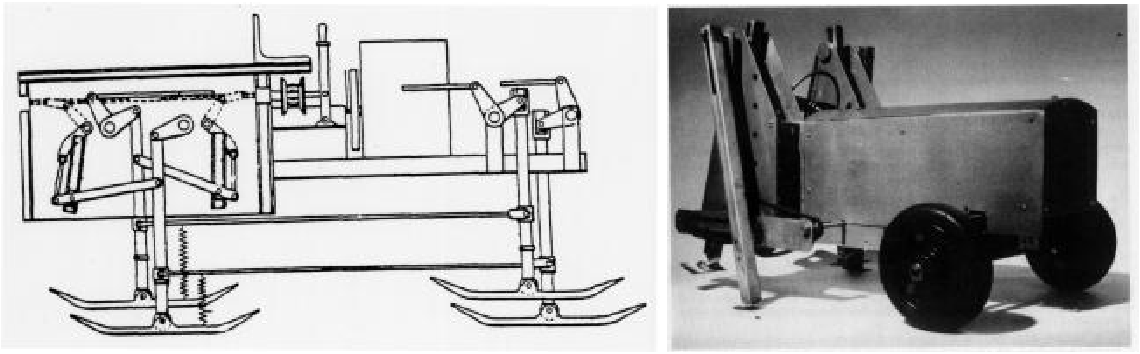

Figure 3: Bechtolsheim Baron quadruped machine (left) and legged tractor prototype (right)

In 1913 the Bechtolsheim Baron patented a quadruped machine whose project is presented in Figure 3. Once again, there is no indication that this machine has actually been built.

An example on a hybrid machine (with wheels and legs) is presented in Figure 3 and dates from the First World War. This prototype was developed by Thring, but has never passed that phase.

Has seen, the previous ideas searched for a mechanism that allowed the movement when powered by an energy source. However, this approximation had a severe limitation: the solution based in gears, to transmit the movement to the legs, was restricted to the adoption of a fixed gait, with the foot placement on the ground at regular intervals. This did not allowed to take advantage of the major advantage of these vehicles, namely the possibility to cross irregular terrains. A second problem was the fact that the information on the machine and the environment state was not being used for its control.

3.2 First Scientific Studies / Implementations

The first documented scientific study on animal locomotion is due to Eadweard Muybridge, which studied the gaits of horses from photography's of trotting horses. The results of this work were published on the Scientific American journal in 1878. After this initial study, Muybridge devoted himself to the gait analysis of forty other mammals, including the ones of human beings.

In the mid 1950's, a number of research groups started to study and develop walking machines in a systematic way. About a decade later, walking machines began to be designed and built by different groups in laboratories.

In 1960, an extensive study of linkage mechanisms for legged locomotion was undertaken by Shigley (Shigley, 1960). In that paper, he proposed several mechanisms which could be used as legs for walking machines. These mechanisms included four-bar linkages, cam linkages, pantograph mechanisms, etc. He also built a vehicle with four rectangular frames. Each frame served as a leg and was nearly as long as the body. The legs were moved in pairs and the stroke was short enough to ensure static stability. The motion of the legs was controlled by a set of double-rocker linkages. Although it did function, it required non-circular gears for uniform velocity of foot motion and was found to be not practical (Song and Waldron, 1989).

In the early 1960's, Space General Corporation developed two walking machines in order to explore the concept of legged locomotion for a lunar rover. One of these was an externally powered, six-legged machine, while the other was a self-contained, eight-legged machine. The leg motions of both machines were coordinated by cams and transmitted by linkages. These vehicles were quite effective within their design goals. The eight-legged machine could turn on its own length using a form of skid steering. The terrain adaptability was poor, however, due to lack of the necessary degrees of freedom (Song and Waldron, 1989).

One of the first vehicles that was able to adopt different gaits was the General Electric quadruped (Figure 4), developed by R. Mosher and finished in 1968 (Liston and Mosher, 1968; Mosher, 1968). This vehicle, with 3.3 m height, 3 m long and 1400 kg weight, presented four legs with three dof (one in the knee and two in the hip), being each joint actuated through an hydraulic cylinder and propelled by a 68 kW internal combustion engine. The machine control was dependent of 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. The vehicle control was demanding (twelve dof), and for this reason few people were able to operate it, getting tired after a while. Although its ability to surpass obstacles and its good mobility in difficult terrains, it became clear that it was needed a computer control system.

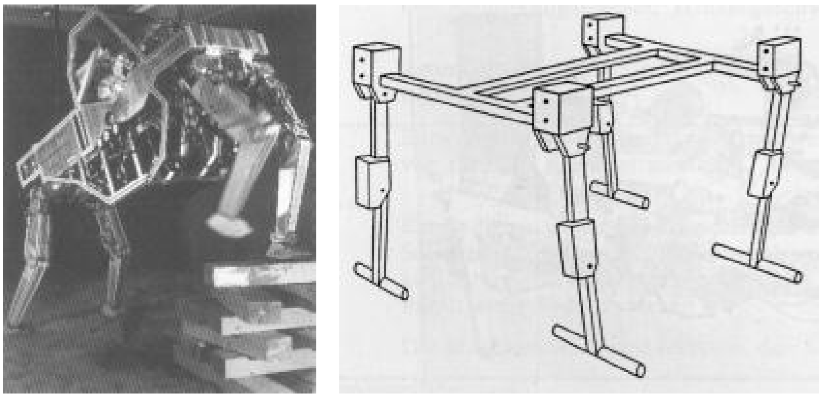

Figure 4: General Electric quadruped (left) and Phoney Poney quadruped (right)

Figure 5: Big Muskie

The Phoney Poney (Figure 4) was developed by McGhee and Frank around the same time (McGhee, 1966; Frank, 1968). This quadruped, completed in 1966, was the first legged robot to move autonomously under computer control and with electrical actuation. Each leg had two degrees of freedom (dof), being each of its joints actuated through an electrical motor (with external power) and a speed reducer. The joint coordination was performed through simple digital logic and presented two different gaits. Its main limitation was the fact that it only moved in straight line, not being able to turn.

Last, it should be referred the Big Muskie (Figure 5), the biggest legged locomotion machine developed until today (15.000 tones) (Cox, 1970). This machine, built by Bucryus-Erie Co. in 1969, for use in an open air coal mine, had four hydraulic actuated legs. When it moved, the four legs raised the body and moved forward or backward one stride and then lowered the body to 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.

Although some of the previous seen machines were able to walk in laboratories and demonstrate some mobility in controlled conditions, none exhibits any of the advantages mentioned above in a practical sense. The reasons for this slow progress mainly arise from the complexity of leg coordination control, the limited understanding of walking gaits and the lack of the development of practical machine legs.

4 Present Day Legged Locomotion Vehicles Examples

After studying the early evolution of robotic locomotion systems and the problems that affected the first machines (and that still affect in a variable degree today's vehicles), in the sequel is presented its recent evolution, referring several present day vehicles, which may be considered as milestones in legged locomotion systems.

The following description is organized by the number of legs of locomotion systems, starting with monopod systems, followed by biped systems and concluding with quadruped and multilegged systems (that are grouped under a single set).

4.1 Monopod Robots

In case of one leg robots the locomotion is performed through hops. Therefore, these machines are also known as hopping robots. Although the most approximate natural example of hopping locomotion is the kangaroo, this model can also be applied to running bipeds, which alternate between one or no foot in contact with the ground. These machines keep an active balance as they move, getting a dynamic stability, allowing a better understanding of the energy exchanges that occur along a locomotion cycle, and emphasizing the active and dynamic stability problems, without requiring leg coordination schemes.

Matsuoka was the first to build a machine according to these concepts, which means, with ballistic flight periods on which the feet loose contact with the ground. His objective was to model the cyclic jumps in human locomotion. In order to achieve this objective, Matsuoka formulated a model, consisting on a body and a weightless leg (to simplify the problem), and considered that the support phase duration was short when compared with the ballistic flight phase. This gait, on which almost the entire cycle is spent on the transfer phase, minimizes the inclination influence during the support phase (Matsuoka, 1979).

To test the control system, Matsuoka built a planar one leg hopping machine. The machine stands over an inclined table (10º with the horizontal), rolling on ball bearings. An electrical solenoid gave a fast impulse to the foot, in such a way that the support period was small. The machine hoped on place with a period of 1 hop.s^{-1} and could walk forward and backward over the table.

Raibert also devoted himself to the study of dynamical locomotion systems and, in 1983, built at Carnegie Mellon University (CMU) a hopping robot. This system, formed by a body and a single leg, needed to hop continuously in order to keep balance (Raibert, 1986).

The body constituted the main structure that transported the needed actuators and instrumentation for the machine operation. The leg could be extended, varying its width, and was equipped with springs along its axis. Several sensors measured the body inclination angle, the hip angle, the leg width, the spring leg stiffness and the ground contact. This first machine 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, named Pogostick (Figure 6), had an additional hip joint to allow the leg moving sideways, as well as front and back. During operation, this robot balanced itself while hopping, moving at a maximum speed of 2.2 ms^{-1}. A cable connected the machine to the electric power supply and to the control computer. For this machine, the running / hopping cycle presented two phases: support (the leg supports the body weight and the foot remains on a fixed location on the ground) and flight (the centre of gravity moves ballistically with the unloaded and free to move leg). Its control was implemented through a small set of simple algorithms (Raibert, 1986). More recently Raibert and colleagues built a biped system and a quadruped system based on the same type of control algorithms (Raibert, 1986).

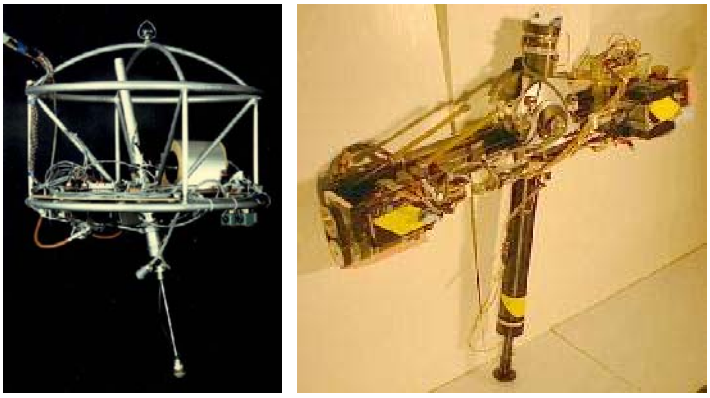

Figure 6: Pogostick (left) and ARL Monopod II (right) monopod robots

ARL Monopod II (Figure 6), with two dof and electrical actuation, is a more recent example of this sort of machines. This robot presents two parts: the body (that carries the sensors and actuators) and the leg (that allows the displacement). The ARL Monopod II possesses an electrical motor that actuates a lead screw, as well as a storage / recovery energy system through springs (Buehler, 2001).

Different from the systems just described, that have a prismatic dof in the leg, Schwind and Koditschek (1997) presented a monopod robot with two actuated rotational dof in the leg. More recently, Hyon and Mita (2002) developed a hopping robot by has three rotational dof in the leg, being one of them passive. The adopted configuration in the legs of these hopping machines presents a better approximation to the animal's legs, allowing this way a viewpoint to the study of the legs biomechanics of living beings. Monopod robots that use the hopping principle for their locomotion are also being developed, adopting mechanisms that allow them to maintain balance when stopped, namely feet with a special geometry (Iida, *et al*., 2002).

At first sight one may think that there are no practical applications for equipments with this configuration. However, the reality is quite different. These robots allow jumping over obstacles or positioning themselves in places where available places for feet placement exist, without worrying with the static stability. For example, it should be mentioned that in 1945 Wallace patented a "hopping" tank (Wallace, 1942). According with him, the fact that the tank moved with only a leg would lead to an erratic trajectory and, therefore, would be difficult to be shot by the enemy.

A potential application for these robots is the exploration of small celestial bodies (satellites, asteroids, comet nucleus), where legged and wheeled robots are not able to move successfully, due to the reduced local gravity (Shimoda, *et al*., 2004). In this perspective, in 1967 Seifert proposed the use of this kind of vehicle, that he named Lunar Pogo, as an efficient locomotion mean of astronauts on the Moon (Seifert, 1967).

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 (Kemurdjian, *et al*., 1995). This 45 kg robot was able to move through hops, perform scientific experiments and transmit the collected data and the experiments results to the Earth through a radio communication channel.

After seeing the monopod robot evolution, in the following subsection the corresponding evolution of biped systems is analysed.

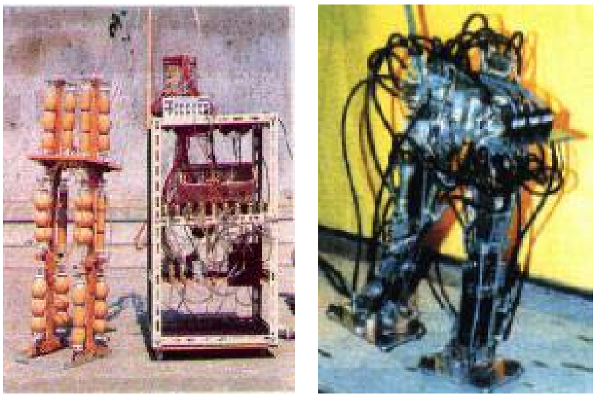

Figure 7: Biped robots WAP-1 (left) and WL-9DR (right)

4.2 Biped Robots

The research in biped locomotion, when compared with the multilegged case, has advanced slower due to the difficulty in establishing a stable control (Katić and Vukobratović, 2002), because biped robots are more demanding regarding its dynamic balance. In spite of this fact, encouraging results have recently been achieved, among which the development of biped robots that reach the running phase (Nagasaki, *et al*., 2003).

Since the end of the 1960's the Waseda University, in Japan, has developed a series of computer controlled biped systems. In 1969 Ichiro Kato developed the biped robot WAP-1 (Figure 7) 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. The main initial limitation of these machines was its low speed, needing 90 s in order to complete a step. Latter advancements allowed reaching speeds near those achieved by the human being.

In the beginning of the 1980's, Kato and his co-workers built the biped WL-9DR that walked with a quasi-dynamic gait (Ogo, *et al*., 1980; Kato, *et al*., 1983). This machine presented ten hydraulic actuated dof and two relatively large feet (Figure 7).

This system adopted a static locomotion mode, moving along a pre-planned trajectory, in order to keep the centre of gravity inside the support base supplied by the support foot. However, once on each locomotion cycle, the machine temporary unbalanced itself (leaning forward) in order to rapidly transfer support from one foot to the other. Before the end of the transfer, the front foot positioned itself in order to make the machine passively return to equilibrium, without needing active control. In 1984 this machine was controlled through a quasi-dynamic gait, taking around one minute to perform a dozen 0.5 m steps (Takanishi, *et al*., 1985).

Nowadays there is a large variety of biped robots presenting humanoid shape and having good locomotion capabilities.

One of the biped robots presenting better locomotion capabilities is the Honda Humanoid Robot (Figure 8). This robot project began in 1986 and the key ideas adopted for its development where "intelligence" and "mobility", since the robot should coexist and cooperate with human beings. The development of the Honda Humanoid Robot was based on data retrieved from human locomotion.

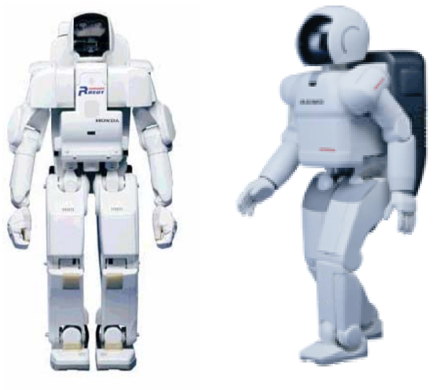

Figure 8: Honda Humanoid Robot – model P3 (left) and ASIMO (right)

Honda's idea was to create a robot that could be used in dairy life, in opposition of a robot developed for a particular application, aiming its introduction in factories (Hirai, *et al.*, 1998). Honda also specified three functions that had to be fulfilled: the locomotion speed should correspond to that of a human being (approximately 3 kmh^{-1}), the robot structure should be prepared to support arms with hand and should be able to climb up and down stairs.

The latest version of this robot, so called ASIMO (Advanced Step in Innovative MObility) model, was concluded in 2000, having 1.2 m height and a 43 kg weight (HTTP#2). The ASIMO has 26 dof, electrically actuated, and can hold 0.5 kg on each hand. It is a completely autonomous robot, either in terms of processing capability, either in terms of power (it transports on its back batteries that allow 15 minutes autonomy).

Sakagami, *et al.* (2002) present an evolved version of the ASIMO model, prepared 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 the interaction with human beings.

The WABIAN (WAseda BIpedal humANoid) biped robot (Figure 9) is another example of biped robots that have been developed in Japan. The main objective of this robot development was the creation of an anthropomorphic robot sharing the same work space and presenting thought and behaviour patterns similar to those of the human being (Yamaguchi and Takanishi, 1998). 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.

This biped robot, with 43 dof, 136 kg weight and 1.97 m height, was electrically actuated. The head presented the capability to gather visual information (through a stereo artificial vision system) and audition. The electrical power was externally supplied being, however, all the processing and computing system integrated on the robot itself (HTTP#2).

To further increase the similarity with the human being, on this robot the hip joints were antagonistically actuated and with variable stiffness, on a similar way to the human joint actuation (each human joint is actuated by two or more muscle groups that present characteristics identical to non-linear 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 (Yamaguchi, *et al.*, 1999).

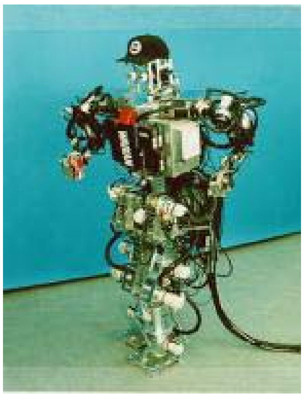

Figure 9: WABIAN humanoid robot

The huge increment that has been verified in the research on biped locomotion in the last years is partially due to the implementation in Japan of the HRP – Humanoid Robotics Program. The main objective of this program, launched by the MITI – Ministry of Economy, Commerce and Industry of Japan between 1998 and 2002, was similar to the followed in the development of the biped WABIAN.

One of the examples of biped robots that have been developed under this program is the HRP-2 humanoid (Humanoid Research Project) (Kaneko, *et al*., 2004). This robot is able to move on irregular surfaces, at 2/3 of the normal human speed, and it is able to cross narrow passages, modifying its gait for that purpose (Kanehiro, *et al*., 2004). In case the robot looses balance and falls, besides the fall being controlled in order to minimize eventual damages on the structure, it still is capable of rise alone (Fujiwara, *et al*., 2003).

In the area of humanoids it is worth mentioning the Kenta robot, which presents the characteristic of being totally actuated by “tendons” and possess a flexible “spinal column” through the use of ten rotational joints (Mizuuchi, *et al*., 2002).

Finally, it should be mentioned the robot Johnnie whose objective is to achieve running phases in the three-dimensional space (Pfeiffer, *et al*., 2003). However, on its present state of development it is only able to walk up to a maximum speed of 2.4 kmh^{-1} (Lohmeier, *et al*., 2004).

4.3 Multilegged Robots

The main aspects of the development of artificial locomotion systems with more than two legs are presented in this section. Since most legged robots ever developed fall into this category, only three legged vehicles are going to be referred here. Its choice was made considering that these machines are often considered success cases, based on the proposed project objectives.

After this section, will be analysed legged robots for specific applications as well as the research lines that are being followed in the development of these sorts of systems. Several other examples of artificial locomotion systems with four or more legs will be presented there.

The first robot to be mentioned is the Adaptive Suspension Vehicle (ASV). This vehicle was developed at the Ohio State University, together with the University of Wisconsin and the Environmental Research Institute of Michigan, and was concluded at the end of 1985 (Figure 10) (Song and Waldron, 1989).

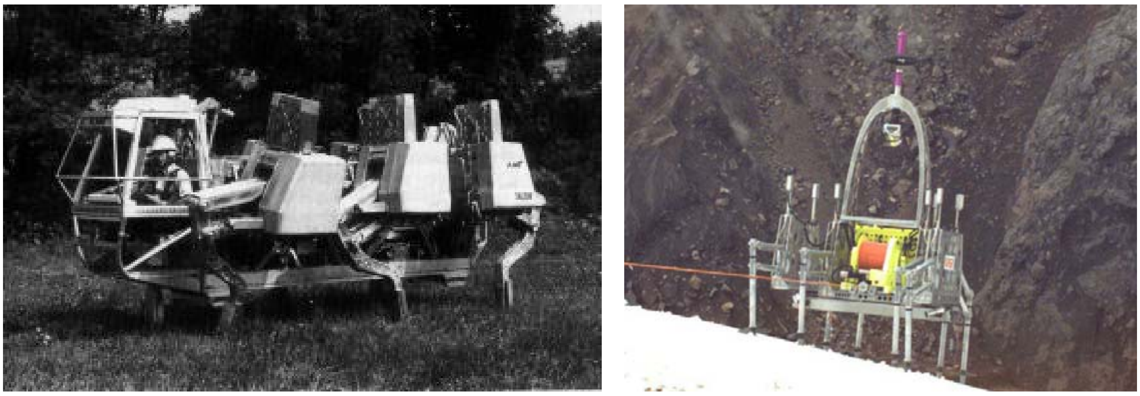

Figure 10: ASV hexapod robot (left) and DANTE II eight-legged robot (right)

This vehicle, with 2720 kg weight and 5.6 m long, presents hydraulic actuation being powered by an internal combustion engine. For its operation there is the need of a human operator that performs the manoeuvring and vehicle state supervision tasks. The operator controls the vehicle locomotion speed and direction through a joystick, but the individual control of each leg is assured by a central computer. The ASV also possesses an optical radar to study the terrain in front of it and to decide on the front foot placement.

As main characteristics, it should be mentioned the 250 kg payload capacity, the possibility to negotiate a maximum slope of 60%, surpass 1.8 m width ditches, climb vertical steps with 1.65 m maximum, surpass isolated walls with 1.35 m height and reach a 2.3 ms^{-1} maximum speed in regular terrains.

A second robot that may be considered a success case is DANTE, developed by the CMU Field Robotics Center. The application of DANTE II robot (Figure 10) is volcanoes exploration. DANTE II was used with relative success at Mount Spurr (Aleutian Range) volcano exploration in Alaska during July 1994 (Bares and Wettergreen, 1999).

This eight-legged robot is electrical actuated, being the power external supplied through an umbilical cord that also serves as a communication structure and rescue cable. Therefore, DANTE II is able to descent the crater walls in a way similar to rappel, in order to gather and analyse high temperature gases from the crater ground.

Besides contributing for volcano exploration advancement, another primary objective of this robot is to show the possibility of extreme environments robotic exploration, such as the ones found on planetary surfaces.

A third case to be mentioned is the Walking Harvester (Figure 11). This hexapod is under development by Plustech Oy Ltd for forestry works.

This vehicle has three hydraulic actuated dof on each leg, and is fed from a diesel engine, allowing it to reach a 1 ms^{-1} maximum speed. For its manoeuvring it is needed a human operator that controls the machine through a joystick. Although it is not commercially available yet, this prototype was already awarded several times.

4.4 Application Specific Legged Robots

Three examples of multilegged artificial locomotion systems, with different leg numbers, have just been presented. In the sequel two areas for which legged locomotion robots with specific characteristics have been developed, cases of pipe inspection robots and climbing robots, are analysed.

Figure 11: Walking Harvester hexapod robot

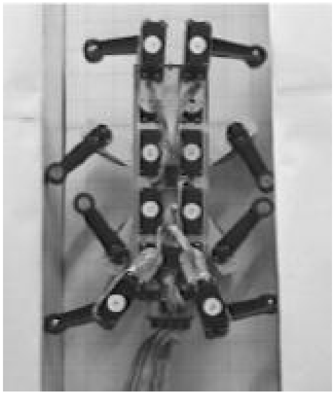

Figure 12: Pipe Climbing Robot

4.4.1 Pipe Inspection Robots

A potential application area of legged robots is in pipe tubing inspection. There are already some robots devoted to these tasks, having wheeled or tracked locomotion, or that float on the medium where they are inserted in. However, systems that use these locomotion schemes suffer from problems related to the lack of traction, with the difficulty on crossing obstacles, or with negotiating pronounced slopes in the tubing (Hertzberg, *et al*., 1998).

As an example of pipe and tubing inspection robots, using legs for its locomotion, it may be referred the Pipe Climbing Robot (Figure 12). This robot, developed by SIEMENS A.G. in 1995, presents an electrical actuation, having eight legs with two dof each.

For its locomotion, the robot pushes two opposite legs against the pipes internal surface, in a way to get stuck, and afterwards moves the body in the movement direction. Although it presents a 0.3 ms^{-1} maximum speed only possesses a 700 g payload capability.

The MORITZ robot (Figure 13) is under development at the Technical University of Munich (TUM). This robot is able to climb through the interior of pipes with different slopes (from horizontal up to vertical) and with curves, and is able to negotiate different structures and junctions among pipes (Zagler and Pfeiffer, 2003). The MORITZ has eight legs (four on each body extreme), each with three dof, being one passive and two DC motor actuated. The theory used for its locomotion is the same as with the Pipe Climbing Robot. It reaches a 0.1 ms^{-1} top speed having a 15 kg payload capability.

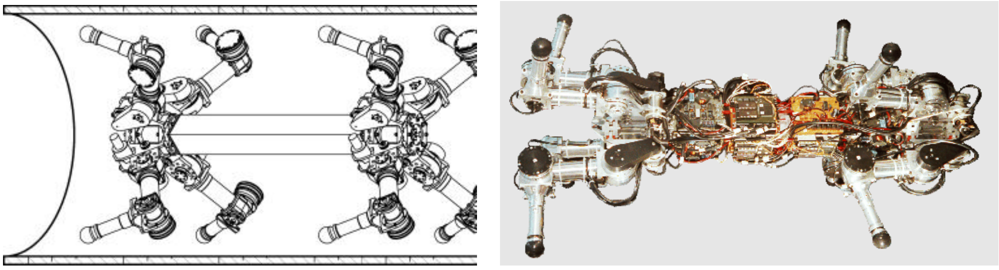

Figure 13: Pipe inspection robot MORITZ

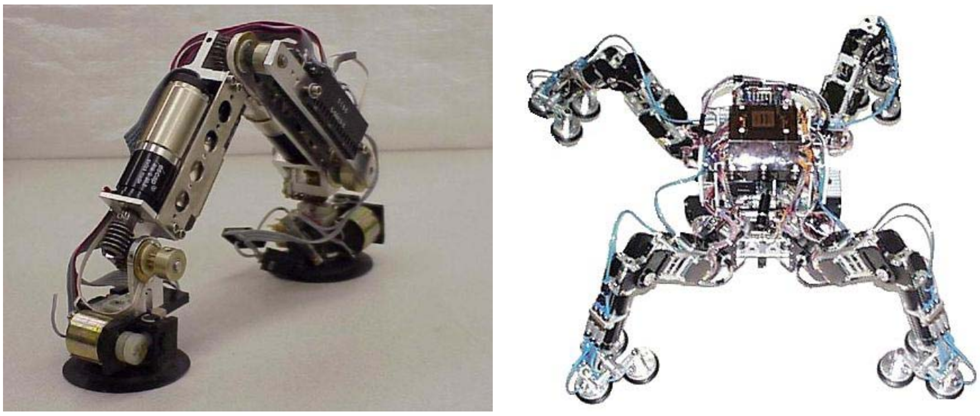

Figure 14: RAMR1 (left) and MRWALLSPECT-III (right) climbing robots

4.4.2 Climbing Robots

Climbing robots constitute another category of legged locomotion robots. These robots can be used in the technical inspection and failure or breakdown diagnosis in dangerous environments. These tasks are necessary in the outside of tall buildings, nuclear power plants or pipelines, reservoirs, chemical, oil and gas industries, planes, ships, in civil construction repair and maintenance, in the prevention and fire fighting actions, or in cleaning operations in sky-scrapers and in the transport of loads inside buildings (Minor, *et al*., 2000; Elkmann, *et al*., 2002).

Simpler alternatives to legged robots usually make use of sliding segments, with suction cups that grab to surfaces, in order to move.

Structures having from two up to eight legs are predominant for the development of these tasks. The adoption of a larger number of limbs supplies redundant support and, frequently, raises the payload capacity and safety. These advantages are achieved at the cost of increased complexity, size and weight. Therefore, when size and efficiency are critical, a structure with minimum weight and complexity is more adequate. For these reasons the biped structure is an excellent candidate.

Presently there are many biped robots with the ability to climb in surfaces with different slopes (Minor, *et al*., 2000). For example, Tummala, *et al*. (2002) propose the adoption of a biped climbing robot for inspection tasks in surfaces with different slopes. This robot, named RAMR1 (Reconfigurable Adaptable Miniature Robot), has feet with suction cups to grab the surfaces where it moves (Figure 14). The use of an under-actuated structure (the robot has five dof actuated by three motors) leads to reduced dimensions and a low weight.

Besides, the RAMR1 presents not only the ability to move on surfaces with different slopes, but also the capability of climbing walls and moving on ceilings.

When there is the need for increased safety and payload capacity, usually are adopted quadrupeds and robots with a larger number of legs. The control of these, typically, very large robots, is more complicated.

As an example of robots with this structure, it is presented in Figure 14 the MRWALLSPECT-III robot (Multifunctional Robot for WALL inSPECTion – Version III) (Kang, *et al*., 2003). This robot has four legs and was designed to transport a video camera and an ultra-sound tool (intended to perform non-destructive tests in industrial structures). Each one of the legs has three DC motor actuated dof and one passive dof, at the ankle joint, implemented using a spherical joint.

The suction force, to keep the robot holding over the structures where it moves, is guaranteed by three suction cups placed on each foot and symmetrically arranged, to which six other vacuum cups placed in the bottom of the body join to help in suction. Four parallel connected vacuum pumps generate the vacuum to guarantee suction.

Regarding its locomotion capabilities, this robot is prepared for climbing walls and different slope surfaces and to, autonomously, change from a surface to another. For example, MRWALLSPECT-III is capable of moving from the floor to a wall and from a wall to the ceiling, being able to negotiate concave or convex shape surface junctions.

5 Legged Robots Research Lines

In this section are presented some of the approximations that have recently been implemented by legged locomotion robots.

5.1 Biological Approximations

It is straightforward to see that even the most advanced robots reveal much inferior performances than their biological counterparts. Animal locomotion is much more versatile, efficient and elegant. For these reasons it is reasonable to consider biological systems in order to apply their schemes in the control of mechanical robots.

For these reasons, there has been an investment in the development of robots that are mimics, as close as possible, of animals. There exist already (or are under development) mechatronic mimics of the most varied animals such as the cricket (Birch, *et al*., 2000), the lobster (Ayers, *et al*., 2000a), the chicken (Mederreg, *et al*., 2003), the gorilla (Kajima, *et al*., 2003; Davis, *et al*., 2003), the dog (Davis, *et al*., 2003; Peng, *et al*., 2003) and the Hermann Turtle (Hennion, *et al*., 2005). For example, the Lobster Robot, that intends to be a lobster mimic, is presented on Figure 15.

Other authors, although not accomplishing exact mechatronic mimic of animals, use them as inspiration for robot construction. Among these stand out the locomotion systems based on dinosaurs (Takita, *et al*., 2000; Takita, *et al*., 2003), spiders (Schulz, *et al*., 2001), centipedes (Kim, *et al*., 2002; Long, *et al*., 2002), octopuses (Nakai, *et al*., 2002), dears (Berns, *et al*., 2003), scorpions (Klaassen, *et al*., 2003), dogs (Iida and Pfeifer, 2004) and ants (Lewinger, *et al*., 2005).

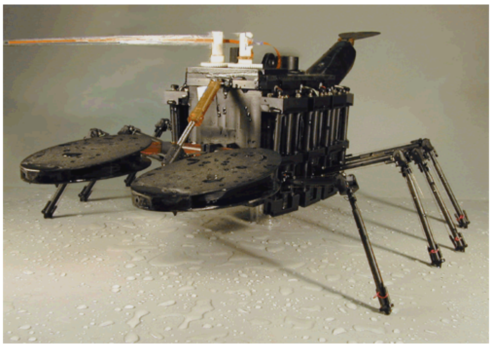

Figure 15: Lobster Robot intended to be a lobster mimic

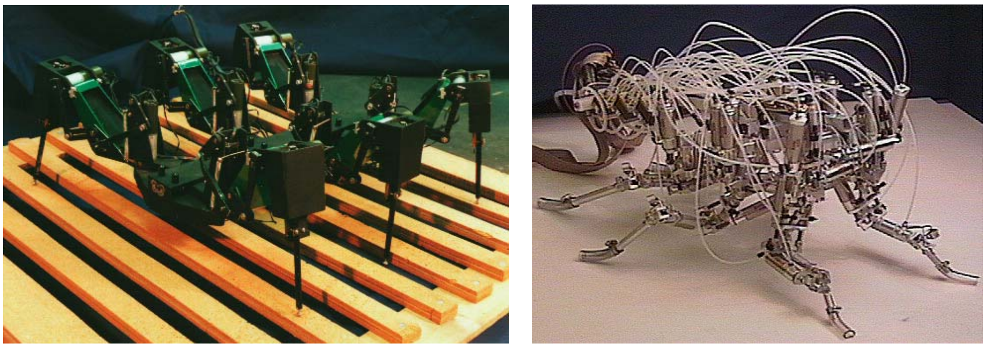

Figure 16: CWRU II (left) and CWRU III (right) hexapod robots

Among the animals that have been "copied" the insects are the most popular, namely the stick-insect (Cruse, *et al*., 1991; Pfeiffer, *et al*., 1995; Kerscher, *et al*., 2004) and the cockroach (Binnard, 1995; Nelson, *et al*., 1997; Nelson and Quinn, 1998). In particular, the stick-insect (*Carausius Morosus*) is often used as a model because it moves skilfully on irregular terrains, while presenting a very simple kinematic structure (Cruse, *et al*., 1991). It should be associated with this the fact that there is also a huge variety of information available on the stick-insect behaviour and control, that may be used for the technical design of artificial locomotion systems based on this animal. The cockroach has been chosen since it presents remarkable running (the *Americana Periplenita* cockroach is considered to be one of the fastest land animals, using the relation speed / body length) and obstacle crossing capabilities (Cham, *et al*., 2002), to which should be coupled the fact that there is also a considerable knowledge on its biomechanics and control.

One of the institutions more engaged on this field is Case Western Reserve University (CWRU) that has already developed several robot prototypes, intended to be insect mechanical copies. The CWRU Robot II is one of such prototypes and represents a stick-insect mimic (Figure 16). This is a hexapod with three active rotational dof (actuated through DC motors) and a translational passive dof (actuated through a pre-tensioned spring) on each leg. This robot is able to implement a variety of walking patterns, based on the insect gaits, and can cross irregular terrains using a distributed controller based on the mechanisms that are thought to be responsible for the leg coordination on stick-insects.

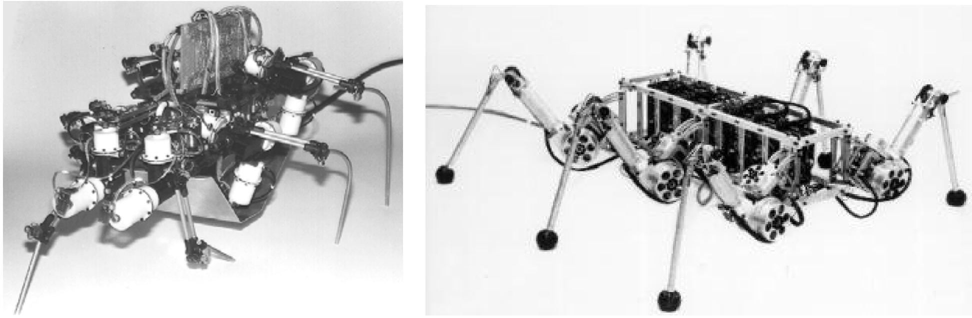

Figure 17: Boadicea (left) and TUM (right) hexapod robots

On the other hand, the CWRU Robot III (Nelson, *et al*., 1997; Nelson and Quinn, 1998) intends to be a mimic (17:1 scale) of the *Blaberus Discoidalis* cockroach (Figure 16). This robot is actuated through double effect pneumatic cylinders, assembled in a way to guarantee opposite forces on each joint. Contrary to CWRU Robot II, whose legs are all identical, the CWRU Robot III design reflects the fact that cockroach legs have different functions and structures. Therefore, the fore legs present five dof, the middle ones four and the hind legs three dof.

CWRU is now developing two new prototypes (the CWRU Robot IV and the CWRU Robot V), also based on the *Blaberus Discoidalis* cockroach. These robots have a similar configuration to the previous model, but have a pneumatic actuation based on “muscular actuators” (McKibben actuators or McKibben artificial muscles) (Colbrunn, 2000; Kingsley, *et al*., 2003). The main difference among these two prototypes is their size, being the CWRU Robot V model larger than its ancestors.

The Massachusetts Institute of Technology (MIT) has also developed biological inspired robots. Boadicea (Figure 17) presents aspects based in the *Blaberus Discoidalis* cockroach (Binnard, 1995) and was one of the prototypes that were built. This hexapod presents three dof in the hind and middle legs and two dof in the fore legs. All legs present a pantograph mechanism and the actuators are double effect pneumatic cylinders.

Another example of a robot based on the stick-insect is the TUM robot developed at the Technical University of Munich (Figure 17). This hexapod robot presents the legs geometry and kinematics, the gaits and the control system based on the legs of the *Carausius Morosus* sick-insect (Pfeiffer, *et al*., 1995). Each leg of this robot performs its trajectory planning on an almost autonomous way, using a hierarchical control structure based in three levels. The leg coordination is achieved through information exchange on the state of each of them.

Last, it should be mentioned the AirInsect robot. This robot, based in the stick-insect, presents the particularity of its actuation being performed through McKibben artificial muscles (Kerscher, *et al*., 2004). The artificial muscles are arranged in pairs, in accordance with the antagonistic principle, this way supplying the force needed for joint motion. Its structure is built using carbon fibre tubes in order to reduce the robot weight to a minimum.

5.2 Reduced Actuation Robots

In all robotic applications, the mechanical complexity is one of the largest sources of malfunctions and considerably increases cost.

Figure 18: Hyperion (left) and SCOUT-I (right) reduced actuation robots

Having these concepts in mind, and opposed to the previous cases, another research line is concerned with the problems that the large number of dof impose on legged robots, such as cost, weight, control difficulties and lack of reliability. This approach bets on the development of robots that are further from their biological counterparts, keeping however the concept of legs for the locomotion. This development line bets on the mechanical simplicity and, therefore, promotes robustness.

Yoneda (2001) proposes a theory on this subject and several examples of robots that present reduced actuation, among which Hyperion (Figure 18). These robots have proved being at least as capable as the biologically-inspired machines, in what concerns their ability to negotiate difficult terrains and obstacles.

Buehler, *et al*. (1998) present the SCOUT-I quadruped robot, with only a dof per leg (placed in the hip and actuated by a servomotor), that is able to move straight or curve, climb stairs and run under open loop control (Buehler, *et al*., 1999). More recently, a new version of this robot, SCOUT-II, was developed with legs having a second dof. This additional dof may be passive and prismatic (Papadopoulos and Buehler, 2000) or rotational (Hawker and Buehler, 2000).

Another approximation that is being followed is inspired on the abstract principles of animal locomotion, but where robots only present a functional mimic of the animals on which were based (Quinn, *et al*., 2002; Cham, *et al*., 2002; Allen, *et al*., 2003). According to the authors that propose this idea, it is not practical to try a direct mapping between the morphologies, actuators or control schemes, since the tools used by biology for building systems are basically different from those used by engineers. Therefore, they propose that inspiration come from biology and that the abstract principles of animal locomotion, that make it effective, should be understood, while the concepts should later be correctly adapted to artificial machines.

As an example, it is verified that animal legs are compliant and the resulting energy efficiency allows them to walk for much longer time periods than if their legs were stiff. The practical application of these ideas on locomotion robotics is not new. The CWRU Robot II, the RHex and several biped robots developed by Gill Pratt possess compliance on its legs. However, animals present the advantage of being able to modify their muscle stiffness and therefore their legs compliance, in such a way that allows them to move efficiently at different locomotion speeds.

Figure 19: Sprawlita hexapod robot

Based on these ideas, Cham, *et al*. (2002) developed a hexapod robot, named Sprawlita (Figure 19), which is based on the following abstract principles of cockroach locomotion: auto-stabilizing posture, different leg functions, passive visco-elastic structure, open-loop feed-forward control and integrated construction.

The resulting robot has six passive rotational dof, corresponding to the compliant connection of the leg hip to the robot body. On its turn, each leg has a prismatic dof actuated by a pneumatic cylinder. Each of the legs can be rotated using a servomotor, in order to allow the variation of the direction upon which the leg exerts force over the ground. In this way it is possible to implement different functions for the different robot legs, such as breaking and accelerating. The robot construction is integrated, that is, the servomotors, the cabling and the connectors are inside the body, which was built using shape deposition manufacturing techniques, commonly used for rapid prototyping.

Thanks to the use of these construction principles, the robot presents a robustness higher than usual for robots of this size, as well as the ability to move over regular terrains at a speed near six body lengths per second (Đorđević, *et al*., 2004). The system is also able to move over distinct types of grounds and in terrains with obstacles, without a significant decrease of the speed and without modifying its gait.

Another approximation is defended by Velimirović, *et al*. (1998). These authors proposed the development of robots using Wheel-With-Legs (WWL) for the locomotion on difficult terrains. These WWL are the equivalent to a wheel spokes and, according to these authors, the use of WWL presents an attractive alternative since it represents a compromise situation, on which the intrinsic locomotion speed of legged systems may be increased and the traction capability of wheeled systems may be improved. These researchers abandoned the idea of imitating animal locomotion and tried to incorporate the advantages of both referred structures (legs and wheels). The most significant improvement consists on the elimination of the opposite leg movement, needed during the transfer phase in the locomotion cycle. This idea has recently been recovered by Laney and Hong (2005), under the name of Actuated Spoke Wheel.

A slightly different approach is presented by Saranli, *et al*. (2001), joining together the abstract principle of animal locomotion with the simplification of the Wheel-With-Legs ideas. These authors describe a dynamical stable hexapod robot, named RHex (Figure 20), which only possesses six actuated dof on each “leg” hip, and whose design was based on the ideas of mechanical simplicity as well as computational and power supply autonomy.

Figure 20: RHex (left), Whegs I (centre) and Mini-Whegs (right) reduced actuation robots

This robot consists on a rigid body with six compliant legs, each of them possessing only one independent rotational dof. The legs junction points as well as the joint orientations are fixed in relation to the body and the legs compliance is mainly in the non actuated spherical dof. This configuration allows the use of a tripod gait during forward and backward locomotion. Moreover the system symmetry allows an identical operation with the body upside-down.

In spite of its design simplicity, this robot is able to walk, run and turn on a dynamical stable way, making use of open-loop control strategies, namely by varying the leg recirculation rate and the inter-leg synchronization structure. This robot was subjected to several evolutions, and currently is capable of moving on sloped terrains and of adopting the Pronk dynamic gait (Komsuoğlu, *et al*., 2001), as well as climbing stairs (Moore, *et al*., 2002; Campbell and Buehler, 2003).

The Whegs I, developed by Quinn, *et al*. (2002), makes use of a similar locomotion concept, although its implementation presents slightly different aspects (Figure 20). This robot design was inspired in the abstract locomotion principles extracted from cockroach studies. The machine has six appendices, named Whegs (word resulting from the junction of the words *wheel* and *legs*), consisting on three equally spaced spokes.

The WWL, earlier described, can be seen as the ancestors of Whegs, presenting both technologies similar characteristics and advantages. However, the WWL were intended to have variable lengths (should be individually actuated) in opposition to Whegs, that are passive.

The mechanisms that equip this robot allow it to move over different sorts of terrains and cross small obstacles on a similar way to a cockroach. This robot uses only a DC motor for propulsion and two small servos for direction. The use of passive compliance on its joints allows the adaptation of its normal tripod gait to irregular terrains and its evolution to co-activation in order to climb over obstacles. The basic locomotion control is implemented on its mechanical design. A benefit of this mechanical simplicity is the simplification of the control system. The main disadvantage is its reduced distance from the ground.

According to the authors, the Whegs I is faster than any other legged robot of similar size and can climb over larger obstacles than the wheeled vehicles of similar dimensions. However, the Whegs I also present disadvantages, due to the design simplifications. The existence of three spokes per leg imposes difficulties when the robot needs to pass under obstacles. Another concern is related to the fact that the existence of multiple spokes on a single Wheg may lead to their entanglement in certain sorts of terrains. Besides, the robot can not change its body posture contrarily to insects that make a good use of this characteristic while climbing and crawling.

Figure 21: Mixed locomotion robot Gorilla Robot II

A later version of this robot, named Whegs II, overcame this problem (Allen, *et al.*, 2003). This robot exhibits a body flexion joint actuated through a bidirectional servomotor. This joint allows to the Whegs II robot implement two behaviours observed on cockroaches during obstacles crossing: on one hand, it allows to rise the front part of the body, as anticipation to step climbing, in order to allow an increased reach of the front legs in the vertical direction; on the other, it allows descending the front part of the body, after climbing and obstacle, in order to keep contact between the robot front legs and the superior surface of the obstacle.

A miniaturised version of this robot, with only four Whegs and named Mini-Whegs, was also introduced (Morrey, *et al.*, 2003). This last version presents as main characteristics, comparatively to the base version, its reduced size (9 cm long) and the ability to jump over obstacles that present heights up to 22 cm (Figure 20).

5.3 Mixed and Hybrid Locomotion Robots

During the last years studies have been developed in the areas of mixed locomotion (*i.e.*, robots that present more than one alternative locomotion mode) and hybrid locomotion (*i.e.*, robots with legs and whose feet have wheels or tracks). Through the combination of two or more different locomotion modes, mobile systems present the advantages inherent to each of these locomotion modes.

Regarding the case of mixed locomotion, an actual example is the Gorilla Robot II (Kajima, *et al.*, 2003) presented in Figure 21. This robot, inspired on primate locomotion, shows the possibility of moving on two legs (biped locomotion), over two legs and on the finger knuckles (quadruped locomotion) and still jumping among suspended points, as if it was a primate jumping among trees branches. With these capabilities, this robot can select one out of three possible locomotion modes, depending on the environment on which it moves.

Regarding the case of hybrid locomotion, the advantages of legged and wheeled locomotion have already been mentioned on section 2. It should be remembered, that among the several locomotion modes, wheeled locomotion is usually superior to legged or tracked locomotion, in flat terrains, from the viewpoints of energy efficiency and locomotion speed. However, these last locomotion modes reveal a superior potential to negotiate obstacles.

Figure 22: Biped Type Leg-Wheeled Robot (left) and WorkPartner (right) hybrid robots

Therefore, the ideal is to have vehicles using two, or more, of these technologies and that are able to use them according to the terrain characteristics on which they move. According to Matsumoto, *et al*. (2002), the combination of legs and wheels is potentially advantageous to efficiently perform the locomotion in even surfaces and also to negotiate artificial irregularities, such as stairs or steps. In regular surfaces the robot uses its wheels for locomotion. When it needs to traverse irregular terrains, or to cross obstacles, the robot blocks its wheels (these start working as feet “soles”) and uses its legs for locomotion.

The Biped Type Leg-Wheeled Robot (Figure 22) is a robot that adopts this locomotion principle (Matsumoto, *et al*., 1999). This biped robot presents two telescopic legs with electrically actuated wheels on the extremities. During locomotion on horizontal surfaces it moves using its wheels and keeping static balance. When it encounters obstacles, the robot blocks its wheels and starts moving using the legs, while adopting a dynamic balance strategy. An evolved version of this robot, presented by Matsumoto, *et al*. (2002), presents three locomotion modes: four wheels locomotion mode, two wheels locomotion mode and stair negotiating locomotion mode, for climbing stairs of approximately the same scale as those commonly used by humans.

Another example of this sort of vehicles is presented by Ylönen and Halme (2002). These authors describe the WorkPartner hybrid robot, on which the locomotion may be performed using either wheels (when the terrain is relatively level), or legs (when the terrain is very irregular), taking advantage of each of these locomotion strategies.

Ota, *et al*. (2002) go even further by presenting a hybrid robot with six dof and with the ability of moving through jumps, with legs and wheels and also with the ability of performing tasks with a robotised arm.

The hybrid systems just analysed have a major problem that consists on their high weight. These hybrid vehicles are equipped with actuated wheels and direction and braking systems. The actuated wheels are usually very heavy and present large dimensions, since they need actuators, direction structures and braking mechanisms. Therefore, it is concluded that the installation of these wheels usually increases the vehicle total weight (that, on its own, is usually big) restricting its versatility. Through the installation of passive wheels, or castors, this problem can be avoided.

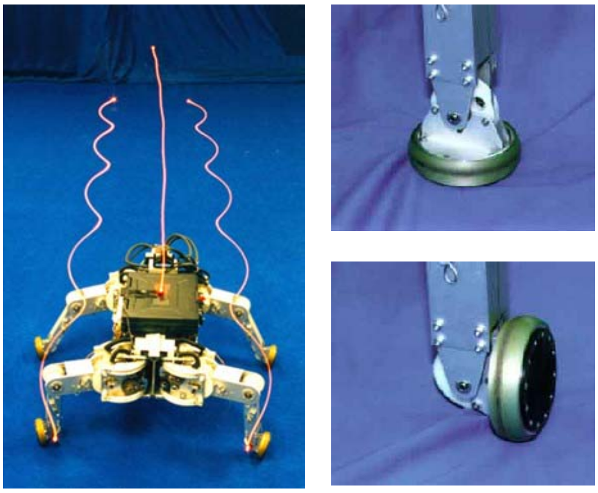

Figure 23: Roller-Walker hybrid robot

Figure 24: AZIMUT hybrid robot

Based on these ideas, Hirose and Takeuchi (1996) describe the Roller-Walker quadruped robot, with hybrid locomotion through wheels, in the legs ends, and on which the wheels are not actuated. The principle through which this robot propels itself during wheeled locomotion is the same as that of the skaters.

As can be seen on Figure 23, Roller-Walker is a vehicle with a special mechanism on the foot, which converts into a sole, in legged locomotion mode, or into a wheel, in skating locomotion mode. On irregular terrain this vehicle moves using its legs and on relatively flat terrains the vehicle skates using its passive wheels. This vehicle has been progressively improved and already possesses the capability to turn while skating (Endo and Hirose, 2000).

On the other hand, Yokota, *et al*. (2003) propose a hybrid quadruped robot that moves through legs and tracks. Finally, it should be mentioned the AZIMUT robot (Figure 24) that presents hybrid locomotion, being able to use wheels, tracks or legs and that, when mixed, allow this robot the adoption of different locomotion modes (Michaud, *et al*., 2003).

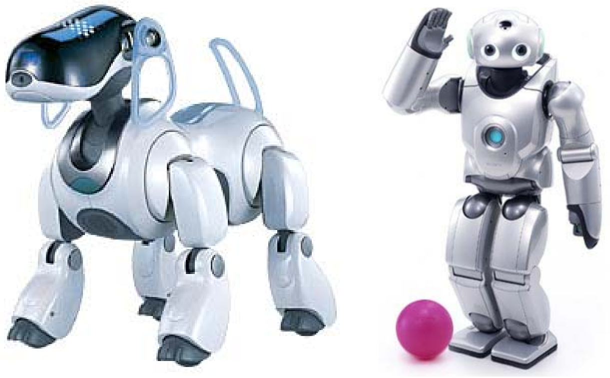

Figure 25: Entertainment robots: AIBO quadruped (left) and QRIO humanoid (right)

5.4 Entertainment Robots

One of the areas on which legged robots have known a great disclosure is the entertainment area. One of the most successful examples is SONY AIBO (Figure 25), a dog inspired quadruped. Although being an entertainment robot this machine is considerable complex, having a total 20 dof and a large variety of sensors (Fujita and Kitano, 1998).

SONY has also a biped entertainment robot, having presented in November 2002 the so-called SDR-4X (SONY Dream Robot) version, meanwhile slightly improved and renamed QRIO – Quest for cuRIOsity in September 2003 (Figure 25) (HTTP#2). SDR-4X, although being a relatively small robot, when compared to other developed biped robots (presents a 58 cm height and 6.5 kg weight), has 28 dof distributed all over its body. In the head it has two CCD (*Charge Coupled Device*) video cameras for the stereo artificial vision system and seven microphones for the sound processing system (Kuroki, *et al*., 2003). The objective of this robot is to be a partner for the human being, being able to behave on a spontaneous way and to understand voice commands issued by its owner (Fujita, *et al*., 2003). In this robot the gait is generated in real time, which allows it to walk in irregular terrains, move adaptively when subjected to an external disturbance force, fall down on a controlled way, making use of pre-programmed movements to absorb the chock, and rise again.

6 Innovative Robots

In this section are presented several robots with legged locomotion that have innovative characteristics, either in their application field, or in the way they adopt locomotion.

We can refer micro-robots with legged locomotion, devoted to micro and nano scale task performance (Ambroggi, *et al*., 1997; Martel, *et al*., 2001; Bonvilain and Chaillet, 2003), legged locomotion robots based in modular systems (Støy, *et al*., 2003; Zhang, *et al*., 2003; Kurokawa, *et al*., 2003) and legged locomotion robots that are based on alternative actuation strategies, such as the use of IPCM (Ionic Polymer Metal Composite) actuators (Kim, *et al*., 2003).

Nakai, *et al*. (2002) describe the implementation of a quadruped robot that, since it can deform, they denominate metamorphic. This robot, whose working principle is inspired in the octopus, has legs built with a low fusion point alloy. When heated the legs literally "melt", deforming and, this way, adapting to the terrain on which the robot is moving. They can even adapt to obstacles and objects that the robot intends to grab. Cooling down the legs, they return to the rigid state and the robot remains with the legs on the given shape until entering on a new warming and cooling leg cycle.

7 Conclusions and Perspectives Towards Future Developments

From what has been seen we can conclude that present day artificial locomotion systems show some important limitations, among which are the reduced power autonomy and the lack of computational capability. In fact, a superior computer performance would allow, in real time, implementing complex control systems and the communication with the robot, whenever the command and control systems are not on the robot to control.

It is also possible to conclude that new generation locomotion systems are characterised by the optimization of existing systems: better actuation systems (Sugahara, *et al*., 2003; So, *et al*., 2003; Hurst, *et al*., 2004), more complex sensorial systems and powerful computers. However, there is still a long way to travel until these systems have comparable capabilities to those revealed by biological systems.

In addition to these implementation difficulties that have been felt, there are still some questions that remain without answer, and whose comprehension may contribute to the improvement of these systems. Among them should be emphasized:

- How do animals keep balance?
- What control mechanisms do animals use?
- How can we obtain the leg actuators control signals that allow the robot to arbitrarily keep a fixed stance, walk or run?
- What is the movement coordination scheme during locomotion?

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