Locomotion for difficult terrain

Freyr Hardarson
Mechatronics Division, Department of Machine Design
Royal Institute of Technology, Stockholm, Sweden

A Survey Study

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1.0 Introduction

Most of the earth's land surface is inaccessible to regular vehicles so there is a need for mobile robots that can handle difficult terrain. Today's robots are mostly designed for traveling over relatively smooth, level or inclined, surfaces. This survey will however discuss different locomotion systems for mobile robots used in difficult terrain. Only robots that use ground contact for propulsion are considered which means that robots travelling through air or water are not included.

The terrain in question is either outdoor environments that are generally considered difficult for mobile robots, such as rough terrain, deserts and arctic areas, or indoor environments where staircases, doorsteps and tight corners can cause difficulties. These robots have applications including forestry, agriculture, (planetary) exploration, fire fighting, radioactive or poisonous areas, disaster or hazardous areas and construction sites. The aim of this survey is to give an overview of what locomotion systems are used and are feasible for mobile robots and give some examples of people that are currently doing research in the area.

Although wheeled and tracked vehicles are by far the most used systems for locomotion, there are several others that have been used. The available locomotion systems can roughly be divided into wheeled, tracked, legged, articulated and hybrid, which is a combination of the former solutions. There are other means of traveling over difficult terrain which will not be discussed here, e.g. excavators use their manipulator to assist them in going over obstacles, up or down steep hills or make their own path. Belforte (1990) and Hirose (1991) discuss locomotion systems in general and give some examples of available robots.

There are a lot of mobile robots available and it is impossible include them all in this survey but here it's tried to give examples of robots that have been successful in travelling over difficult terrain. The report starts with a discussion on the difficult terrain in question and the choice of locomotion systems, followed by a brief discussion on several locomotion systems where some examples are given.

2.0 Difficult Terrain

The term difficult is not a very clear description of the terrain and there is no clear distinction between easy and difficult terrain. The degree of difficulty is also dependent on the properties of the vehicle itself, such as its size and locomotion system. Humans generally consider difficult terrain to be areas such as deserts, rocky areas, swamps and arctic areas but in the case of robots, indoor areas can be just as difficult as they are mostly designed for a walking biped. The degree of difficulty is therefore in the eye of the locomotor.

In places where mobile robots are already in use, such as factories, the environment itself has been structured for the robot but there are still very few robots that have the ability to travel in unstructured and rough environments.

2.1 Terrain Properties

The difficulty of the terrain is dependent upon several properties

- The geometric properties determine the form of the surface, such as its roughness and inclination. This includes obstacles such as steps, holes and ditches.
- Material properties include ground consistency, strength, friction, cohesion, moisture content, density, plasticity index etc. This affects e.g. the sinkage and slipping of the vehicle.
- Temporal properties are time varying changes in the terrain. This can affect both the geometric and material properties of the terrain. E.g. a vehicle traveling over a river where the bottom changes under it due to a strong current or a vehicle that suffers unexpected accelerations from the surface underneath it e.g. robot travelling in a shaking train.

2.2 Vehicle Failures due to Terrain

There are several failures a vehicle can suffer due to the terrain. The typical failures a vehicle can encounter are

- Clearance failures occur when some part of the vehicle chassis hits the ground.
- Vibrations due to variations in the terrain can cause damage to cargo or equipment, and wear to the vehicle itself
- Stability failure where too steep slopes or too high speed over rough terrain, can make the vehicle tip over.
- Traction failures caused by loss of friction or sinkage, e.g. when traveling over ice or muddy soil.

In order to avoid failures it is necessary in some way to classify the terrain according to a vehicles ability to travel over it. This is to help the driver (man or computer) to identify difficulties and determine an appropriate path for navigating over an uncertain terrain.

3.0 Choice of Locomotion System

The selection of a locomotion system is crucial for the performance of a mobile robot and whether it will be successful in its tasks. Some system analysis is needed to define its mission, capabilities, such as speed and stability, and the environment it is meant to travel over. The different alternatives should then be explored, as different types of locomotion systems have different properties, complexity and costs.

3.1 Terrain Specification

As examples of how the terrain can affect the decision, the following examples are given.

- Tanks and snowmobiles are equipped with tracks as they are generally best suited for soft or loose terrain like snow or sand, since they spread out the weight and have a large ground-contact which improves traction.
- In the forest industry it has been found that wheeled vehicles, typically six or eight wheels, have better performance than tracked vehicles, as terrain is rugged. Experiments with a legged harvester have also been done, see Section 6.3.1 on page 9.
- Robots are often used to travel on the seafloor for monitoring and other tasks. Mostly wheels or tracks have been used for these robots, but they often stir up particles that block their cameras and thereby make the robot blind. Therefore legged robots have been suggested as an alternative as legs don’t stir up as much mud.

3.2 Mission Statement

The mission statement is the purpose of locomotion. According to Bekker (1969), it can be divided into its functional and operational characteristics as can be seen on figure 1. The functional characteristics determine whether the robot is supposed to be used for transportation or/and special purposes such as exploration, mining etc. The operational characteristics are e.g. mobility, environment and terrain variations, weight, costs etc.

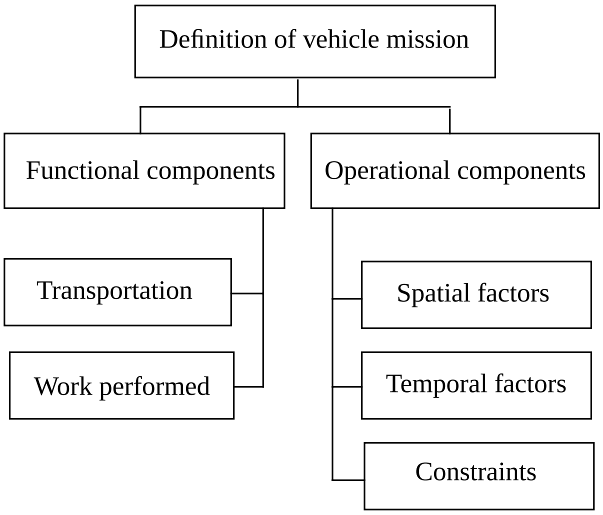

FIGURE 1. Elements of mission definition of a vehicle (simplified from Bekker (1969)])

For a transporter, the weight and size of the cargo has to be described or estimated. The behavior of a transporter can change drastically depending on the amount of payload it's carrying. For a special purpose vehicle, the work performed and the equipment used has to be considered, e.g. size, weight and use of equipment.

The operational components are harder to analyze as the spatial and temporal factors are often interlinked, e.g. the speed is dependent upon the terrain. The constraints on the design are mostly caused by vehicle size, fault tolerance and cost. Another factor is allowed effect on the terrain, e.g. an exploration robot would not be allowed to damage a sensitive ecosystem.

4.0 Wheeled Locomotion

Wheeled locomotion is the most used locomotion system and probably the most studied and advanced. It is superior to any other locomotion system in providing a smooth and energy efficient ride over relatively even surfaces.

The advantages of wheels are

- smoothness and speed in relatively even terrain
- the technology is well developed and simple
- payload-weight-to-mechanism-weight ratio is favorable as is their energy consumption.

The disadvantages of wheels on uneven terrain are

- they generally have trouble if an obstacle is higher than the radius of the wheels.
- wheels follow ground contour which can give trouble i.e. if the ground has steps, holes or ditches.

There are several methods of improving wheeled locomotion in difficult terrain. Multiple wheels improve traction and stability, suspension system and linkages keep ground contact and improve climbing ability over obstacles larger than the wheel radius.

A lot of all-terrain vehicles have been designed for public, industrial and military purposes. Forest machines have a great need for mobility in difficult terrain, carrying large loads. Some of them have active suspension for the cockpit to make the ride easier for the driver. The Hummer jeep used by e.g. the U.S. Military, is a very versatile vehicle with all-terrain capabilities.

4.1 The Mars Microrover

Some of the most interesting wheeled robots that have been designed for rough terrain are probably the planetary rovers intended for exploration on the Moon and Mars.

The Jet Propulsion Laboratory, California, USA, has designed a small planetary rover, see figure 2, that is carried by NASA's Mars Pathfinder lander, expected to land on the planet Mars July 4th, 1997. There the microrover will be deployed and conduct several tests on the Mars surface. The mission is called the Microrover Flight Experiment (MFEX). The microrover weighs 11.5 kg and has a normal height of 280 mm, length of 630 mm, width of 480 mm and ground-clearance of 130 mm. It has six independently actuated wheels, with wheel diameter 130 mm, where the four outer wheels are used for steering. This configuration enables it to turn in place. The wheels are connected to the body through a passive linkage system that kinematically adapts to the ground and allows it to negotiate obstacles twice the wheel diameter. More information can be found in Shirley & Matijevic (1995) and Stone (1993) and updates on its mission at [MFEX].Other planetary rovers are the Lunar Rover and the Nomad rover, built by Carnegie Mellon University

[CMU] and Marsokhod, built by Babakin Centre, Russia, for Mars exploration (Lamboley et al (1995)).

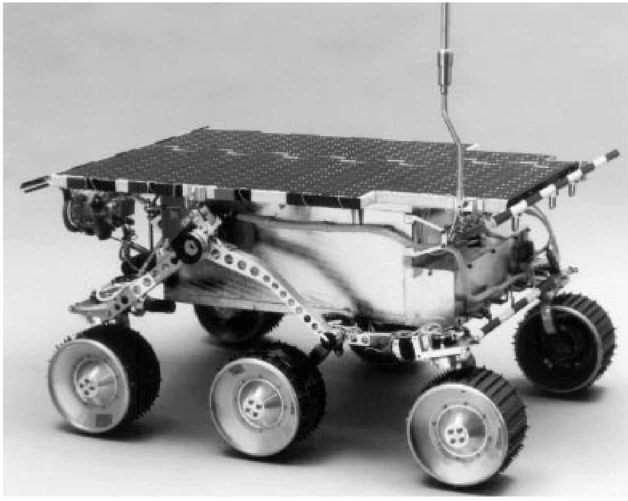

FIGURE 2. The microrover for the Microrover Flight Experiment built by the Jet Propulsion Laboratory [MFEX].

4.2 The Quadru-Rhomb Rover

The Hirose & Yoneda Laboratory, Tokyo Institute of Technology, have designed four rovers for Mars and Lunar exploration. The Hien II, see figure 3, has four wheels arranged in a rhombic shape were the front wheel is equipped with a probe type front suspension with two degrees of freedom as a mechanism to provide adaptation to the terrain without using actuation (Hirose & Ootsukasa (1993),[H&Y]).

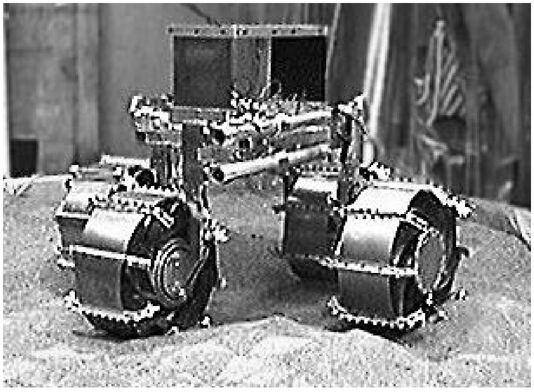

FIGURE 3. The Hien II Mars rover, built by Hirose & Yoneda Lab, Tokyo Institute of Technology [H&Y].

5.0 Tracked Locomotion

Tracks are often considered the most versatile locomotion system and can handle relatively large obstacles and loose soil. Therefore they have been used predominantly in vehicles like tanks and excavators

The advantages are

- smooth locomotion on relatively smooth terrain
- the technology is well understood and simple
- superb traction on loose ground
- can handle large hinders and small holes and ditches
- good payload capacity

The disadvantages of tracks are

- inefficiency due to friction in the tracks
- slip friction when the vehicle must turn.
- not especially gentle with the ground they travel over, e.g. when turning in place
- not adaptive to the ground
- vehicles with one pair of belts suffer from impacts when e.g. climbing over large boulders or when they start going down steep slopes

To compensate for small adaptability, vehicles have been designed with two pairs of tracks which also gives smoother ride.

5.1 Pebble

Pebble is a small tracked robot sold by IS Robotics as a research rover for difficult terrain, both indoor and outdoor, see figure 4. The Mobile Robotics Group at MIT Artificial Intelligence Laboratory has been using Pebble for research on autonomous planetary exploration, see also Section 6.3.3 on page 10. Pebble is sold with forward and rear bump sensors and an inner-mounted ring of IR proximity sensors. Options of radio communication, sonar positioning and a camera with video transmitter are available. More information can be found at [ISR] and [MIT].

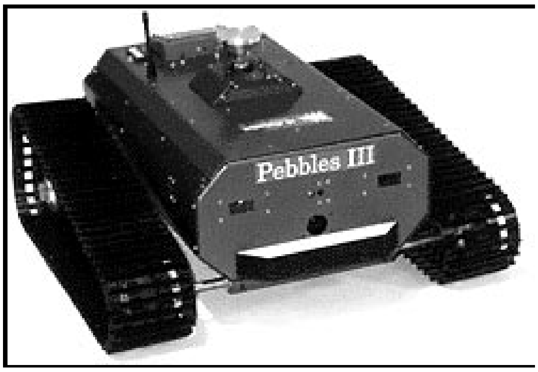

FIGURE 4. Pebble, a small tracked mobile robot by IS Robotics Ltd. [ISR].

5.2 TAQT-Carrier

The Terrain Adaptive Quadru-Track (TAQT) carrier robot and it's predecessor Helios 2, see figure 5, were built at the Hirose & Yoneda Laboratory at The Tokyo Institute of Technology. They employ two pairs of tracks that are pivoted to the body at the middle of the track. This gives better adaptability to the ground and smoother locomotion in difficult terrain. The upper body can be adjusted to keep the center of gravity in the middle and thereby improving the stability of the robot while keeping the cargo in a horizontal position. The total weight of Helios II is 90 kg; and the length, width and height are 1m x 0.6m x 1m respectively.

The TAQT Carrier is designed for transporting materials at construction sites etc., and is commercially available. It uses two electrical actuators for each track and a coupled drive for allowing power of both motors to be used for propulsion and swinging of the track. The total weight is 310 kg (including a 70 kg battery pack), the load capacity is 100 kg and the length, width and height are 1.3m x 0.86m x 0.97m respectively. The design and control of the TAQT Carrier is described in Hirose et al (1990) and more information is available at [H&Y].

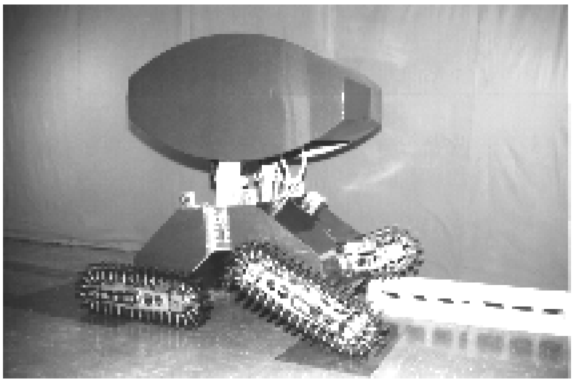

FIGURE 5. The Terrain Adaptive Quadru-Track carrier Helios 2 by the Hirose & Yoneda Lab at The Tokyo Institute of Technology [H&Y].

6.0 Legged Locomotion

Research on legged vehicles has been going on for over a hundred years. The reason for this persistence is that only half of the earth's land area is accessible to wheeled and tracked vehicles while legged animals can be found almost anywhere. One of the main reason for using legged locomotion is stated by Raibert (1986) as follows.

"One reason legs provide better mobility in rough terrain than do wheels or tracks is that they can use isolated footholds that optimize support and traction, whereas a wheel requires a continuous path of support. As a consequence, the mobility of a legged system is generally limited by the best footholds in the reachable terrain and a wheel is limited by the worst terrain."

Advantages of legged locomotion are

- adaptive to uneven terrain
- use isolated footholds
- provide active suspension
- environmental effects of legged vehicles are less than wheeled or tracked vehicles

The disadvantages are

- artificial walking mechanisms are so far heavy due to large number of actuators

- control of walking is very complex and so far walking vehicles are rather slow
- bad payload-weight-to-mechanism-weight ratio compared to wheeled or tracked vehicles
- suffers an impact with each step

A lot of research has been put into legged machines and several successful applications are available but most of them have never been outside a laboratory. Most them don't have on-board computing or energy supply which is therefore provided by a tether.

6.1 General on Legged Locomotion

This chapter aims to give an brief introduction to the basics of legged locomotion with a special emphasize on the mechanical construction. There are a lot of terms used that need explanation for those not familiar with the field. The main difference between walking machines and wheeled or tracked machines is that their ground contact is not continuous, instead they use isolated footholds by coordinated repositioning of their legs, or what is called gait, as will be explained in section 6.1.4 .

Many designers use biological inspiration in their mechanical design, both in the configuration of legs and in the design of the legs themselves. This leads often to simplification of the actual biological systems as they have a larger degree of complexity than is possible or even necessary to simulate mechanically.

Walking machines are classified depending on the number of legs used. The most common are

- Octapods that have eight legs similar to spiders and crabs.
- Hexapods that have six legs similar to most insects.
- Quadrupeds that have four legs similar to most mammals and marsupials.
- Bipeds that have two legs similar to humans, kangaroos and birds.

6.1.1 Leg Configuration

Leg configuration decides how the legs are situated on the body. This affects the stability of the robot and the work space of the legs. There are two main types of leg configurations, that are based on biological counterparts. The main difference is in the way the legs swing with respect to the body.

The first type is similar to cats, humans and birds, where the legs swing around a horizontal axis. Legs are in line, facing in the same direction and support the weight of the body by placing the feet under the body, near the vertical projection of the body's center of mass on the ground. Examples can been seen on figure 10, figure 17 and figure 22 for different number of legs.

The second type is more similar to insects where the legs swing around a more vertical axis. It has a sprawled stance where the legs stretch out from the body and the support is not provided directly under the body, far from center of gravity which make them very stable. This configuration is more common for multilimbed robots such as quadrupeds and hexapods. Examples of a robots with sprawled leg configuration can be seen on figure 11 and figure 12.

Most configurations have the legs distributed symmetrically about an axis in the direction of motion. But in some cases they can be multi-symmetric e.g. figure 13 shows a robot using a sprawled configuration that is symmetric about two axis.

Many other clever leg configurations have been tried that don't have as clear biological coupling. Some examples are given here below.

- Frame walkers
  The body is made of two frame that can slide relative to each other, each frame having a set of legs attached to. The number of legs in each set must be at least three to provide static stability. The forward motion is produced by that the legs of one frame provide support while the other legs are lifted and then the frame is slid in the forward direction where the legs are lowered again. A frame walker is described in section 6.2.1 and can seen on figure 8 (Wettergreen et al (1993)).
- Circulating walkers
  The legs, typically six, are arranged in two stacks where the legs in each stack rotate about the same vertical stack axis. The two stacks are connect by an arched body. When positioning a new leg, one of the rear legs is lifted and rotated through the body to the front. A circular walker is discussed in section 6.2.2 and can be seen on figure 9 (Bares & Whittaker (1993)).

- Weaving walkers
  Are very similar to the circular walkers but the legs are able to rotate them under, over or between the other legs, depending on which leg is being moved, instead of rotating the legs through the body (Bares & Whittaker (1993)).
- Platonic beasts
  An example of a more unusual type are the platonic beasts that have a body made of a spherically symmetric polyhedron with a limb attached to each of it vertex. This gives the possibility of using a rolling gait in addition to the more normal gaits. The limbs, that are not used for support, can be used as manipulators (Pai et al (1994)).

6.1.2 Leg Design

All animals have articulated legs, i.e. they are composed of linkages and joints. Articulated robot legs typically have two to four actuated degrees of freedom, three being the most common as it allows it to position its foot at any place in space. The main problem in leg design is to actuate joints that are out on the leg e.g.a knee joint. The placement of a actuator out on the leg is generally not reasonable as the weight of the leg should be kept to minimum and to reduce its moment of inertia. As the weight and moment of inertia increase, a bigger motor is needed to lift the whole leg which again adds to the weight that the leg has to carry. To avoid this many designers use a system of cables and pulleys, light-weight linear actuators or linkages e.g. a pantograph (Hirose et al (1991b), Berkemeier & Desai (1996), Mennitto et al (1995)).

A pantograph is simple way to have a leg with a knee, that reduces the weight of the leg itself as the actuators can be situated close to the body. Shigeo Hirose introduced the gravity decoupled pantograph (Hirose (1984)) where two linear actuators are decoupled to do vertical and horizontal work which translates the foot in a horizontal or vertical direction depending on which actuator is used. An example of a robot using a pantograph leg can be seen on figure 13 and explained in Hirose (1984) and its further discussed in section 6.4.1 .

Another solutions is to get rid of knee by using prismatic (telescopic) legs. The shortening of a prismatic leg can be seen as equivalent to the bending of a knee of a articulated leg.

Most robot designer try to minimize the oscillation of the body to make the ride as smooth as possible. However animals allow their body oscillate during walking as it gives the opportunity to store energy as will be explained below. According to Alexander (1990), there are four alternative patterns of movement for legs as shown on figure 6. For a smooth body motion the legs have to shorten, either by bending or using prismatic legs, during ground contact, as shown in figure 6(A). In this case, both the telescopic leg and the hip actuator have to do negative work, i.e. do work against the motion of the body, which wastes energy. By using a slider, as shown in figure 6(B), this problem can be avoided. This can be accomplished e.g. by using a gravity decoupled pantograph, as discussed above, that can be almost as energy efficient as using wheels. If the body is allowed to oscillate, as most animals do, the kinetic energy can be stored. In the case of figure 6(C), the leg is stiff (fixed length) and behaves as an inverted pendulum. Kinetic energy is stored as potential energy which decelerates and re-accelerates the body. In the case of figure 6(D) the leg is springy and acts similar to a pogo stick. Kinetic and potential energy is stored as strain energy in the spring which is released again when the leg starts to lengthen.

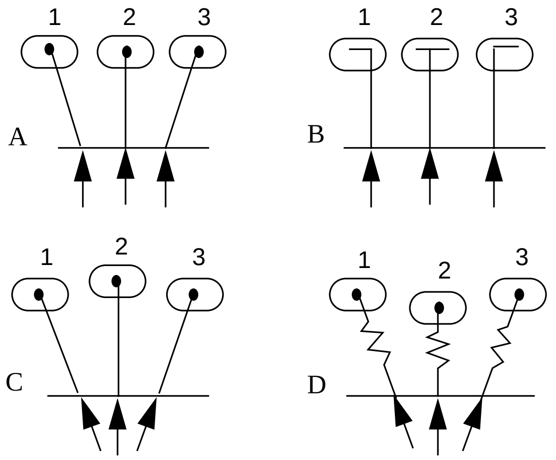

FIGURE 6. Alternative patterns of movement for the legs of robots. The arrows indicate the direction of the reaction force. (A) is a telescopic leg, (B) is a sliding leg, (C) is a stiff leg and (D) is a springy leg (Alexander (1990)).

6.1.3 Stability

The motion of legged robots can be divided into statically and dynamically stable. Static stability means that the robot is stable at all times during its gait cycle, i.e. one gait cycle is when all the legs have been repositioned. Dynamic stability means that the robot is only stable when it is moving. The term quasi-dynamic is used for robots with alternating static and dynamic stability phases during their gait cycle.

For robots with point feet, static stability demands that the robot has at least three legs on the ground at all times and the robot's centre of gravity is inside the support polygon, i.e. the convex polygon formed by the feet supporting the robot. This is explained on figure 7. On the left side, four legs provide support and the center of mass is located inside the support polygon so the robot is statically stable. On the right side the bottom left leg has been lifted, putting the center of mass outside the support polygon which generates a tipping moment.

Dynamic stability demands active actuation to maintain balance, similar to riding a bicycle. This makes greater demand on the control system, but the advantage being that dynamic motion is faster than static motion.

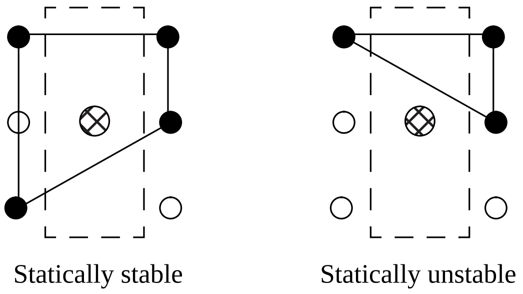

FIGURE 7. Support polygon for a hexapod, statically stable and unstable cases. The center of mass is the slightly larger circle, marked with 'X'. The smaller circles are the feet and are filled if they support the robot.

A way of avoiding stability failure is to equip the robot with feet to provide extra support. In fact most biped robot use this solution as can be seen on figure 20.

6.1.4 Gaits

A gait is the coordinated movement of the legs to produce walking. An animal can have several different gaits at its disposal depending on the speed it wants to travel and the number of legs it uses. The fewer legs, the less variety of gaits. In principal, an animal can use gaits of another animal with fewer legs (Full (1993)).

Bipeds have walking, with alternative single support and double support. Walking can be either statically or dynamically stable, depending on the speed. Dynamically stable gaits are running, with alternating flight and single support as humans and ostriches or hopping, with alternating flight and double support as kangaroos.

A quadruped can have a more variety of gaits due to the greater number of legs. Walking is statically stable gait where one leg is moved at the time and the body shifted to keep the center of mass inside the support polygon. There are a variety of dynamic gaits like trotting, bounding and pacing. Trotting is when diagonal pairs of legs move together and bounding when fore or aft legs move together. these are used by animals like horses, dogs and cats. Pacing is when pair of legs on the same side move together and is used camels and elephants.

A hexapod has a wide variety of gaits, both statically and dynamically stable. The statically stable gaits go from the slow wave-gait, where one leg at the time is lifted and moved forward at the time, to the tripod gait. The wave-gait starts by moving one leg e.g. one of a the rear legs, next the middle leg on the same side is moved and finally the front leg. It then starts again at the other rear leg and moves forward at that side. As the speed increases it will try to have more legs in the air at the same time until it reaches the tripod gait where the front and rear legs of one side and the middle leg of the opposite side provide support. Hexapods can also run dynamically by using gaits similar to quadrupeds and bipeds, or hopping gaits (Full (1993)).

6.2 Dante II and Ambler

The Field Robotics Center at Carnegie Mellon University developed Dante II and Ambler walking robots for extreme terrain. Their design and gaits are different from the robots in later sections.

6.2.1 Dante II

Dante is a tethered teleoperated robot. In July 1994 it descended down the crater of the volcano Mt. Spurr, Alaska, to analyze high temperature gasses from the crater floor. The experiment was successful in most aspects except for that it tipped over on its way back up the crater.

Dante's body had two frames, each of which had four legs attached. The frames were separated by a track, along which the frames could slide relative to each other. The robot walks by alternatively lifting the legs of one frame while keeping the legs of the other frame on the ground and then slide the frame forward and lower the legs again. A tether was attached to the upper frame to help support its weight in steep slopes and supply energy and communications.

Dante II had dimensions length, height and width of 2.4 m x 3 m x 3.6 m respectively and weighed 770 kg. It had a maximum speed of 1 m/min and power consumption in full motion was 1500 W.

FIGURE 8. Dante II by the Field Robotics Center at Carnegie Mellon University, on rim of the crater of Mt. Spurr [CMU]

More information on Dante II and its mission can be found at [CMU] and a description on its predecessor Dante, who in the year 1992 tried to climb down Mt. Erebus in Antarctica but failed, can be found in Wettergreen et al (1993).

6.2.2 Ambler

Ambler is a fully operable, self-contained, autonomous robot that employs a circulating gait. The legs are orthogonal and the actuators produce cylindrical coordinates to the foot placement. Ambler's six legs are arranged in two stacks where three legs rotate about the same stack axis. The two stacks are connect by an arched body as can be seen on figure 9. When positioning a new leg, one of the rear legs is lifted and rotated through the body to the front.

Ambler has dimensions length 3.5 m x height 4-6 m x width 4.5 m, weighs 2050 kg and has a payload capacity of 1000 kg. It has a maximum speed of 0.3 m/s. Its 18 degrees of freedom are driven by permanent magnet DC motors, powered by batteries and a propane generator. It's power consumption is 1900 W. The Ambler is described in Bares & Whittaker (1993).

FIGURE 9. Ambler by the Field Robotics Center at Carnegie Mellon University [CMU]

6.3 Hexapods

Six legged robots are the most common type of legged robots. They have advantage of static stability and redundancy compared to robots with fewer legs but are in general slower.

6.3.1 Plustech Oy

The company Plustech Oy, in Finland, has been developing a walking forest machine for harvesting trees. This is one of few walking machines that have been designed for industrial applications and is fully functional. The harvester has dimensions length 3.5 m x height 3 m x width 2 m and weighs 3500 kg. It has a maximum speed of 1 m/s. Its 18 degrees of freedom are driven by hydraulics and is powered by a diesel engine.

FIGURE 10. Plustech Oy forest machine for harvesting trees [PLU].

6.3.2 The Artificial Insect Project

At Case Western Reserve University, Autonomous Agent Research group, a hexapod robot has been used to study biologically-inspired neural networks. The control of locomotion and behaviors is based on the behaviors of walking stick insects. By designing a neural controller for the legs, a continues variety of gaits were produced, from the slow wave-gait to the tripod-gait. The artificial project is described in Beer et al (1990) and at [CWRU].

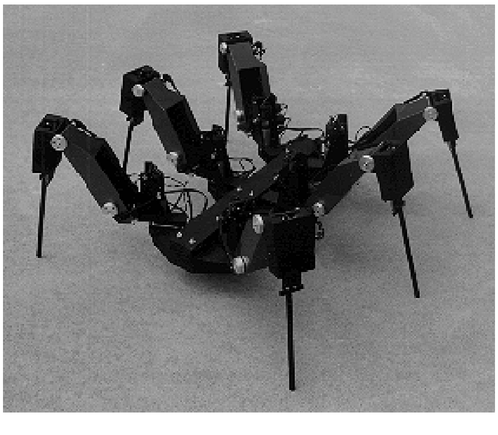

FIGURE 11. The Artificial Insect Project, Case Western Reserve University, Autonomous Agents research Group [CWRU].

6.3.3 Hannibal and Attila

The Mobile Robotics Group at the Artificial Intelligence Laboratory, Massachusetts Institute of Technology (MIT), has built several hexapods, two of them, Hannibal and Attila, where especially built for locomotion over difficult terrain. As many others, they used insect inspiration in their design of structure and control system. The robots are very complicated, having 24 actuators, about 150 sensors and 10 computers. One special feature of Attila is that each leg has four degree of freedom to improve climbing capabilities. Results of their experiments can be found in Brooks (1989) and Ferrell (1994) and general information on the project at [MIT].

FIGURE 12. Attila built by the Mobile Robot Group at Massachusetts Institute of Technology [MIT]

6.4 Quadrupeds

Four legs is the minimum number capable of executing statically stable walk without using feet. For a statically stable gait, a quadruped has to keep its centre of gravity inside the contact polygon when it lifts one leg. They can also use dynamically stable gaits found in animals, like trotting, pacing and bounding.

6.4.1 Hirose & Yoneda Lab

At the Hirose & Yoneda Lab, Tokyo Institute of Technology, several different four legged robots have been built since they started research on walking machines in 1976. In 1980 they introduced a quadruped robot that used three-dimensional pantographs that translate the motion of each actuator into a pure Cartesian translation of the foot. This simplified the kinematic solutions and reduced computer work. By using simple algorithms, like searching behavior, and contact and posture sensors, the robot could negotiate stairs and other obstacles as described in Hirose (1984).

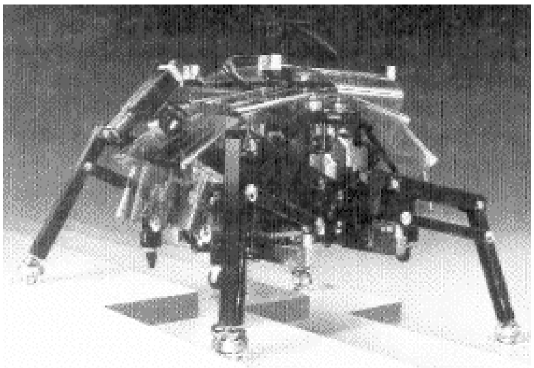

FIGURE 13. Titan IV by the Hirose & Yoneda Lab at The Tokyo Institute of Technology [H&Y].

Since then, they have developed a series of quadruped robots like Titan III, IV, VI,VIII and wall-climbing robots Ninja I-II.

Titan III and IV both use the pantograph leg and Titan IV can automatically switch from a static to a dynamic gait (trot) with a max speed of 0.4 m/s, see figure 13. They are discussed in Hirose et al (1985) and Hirose & Kunieda (1991).

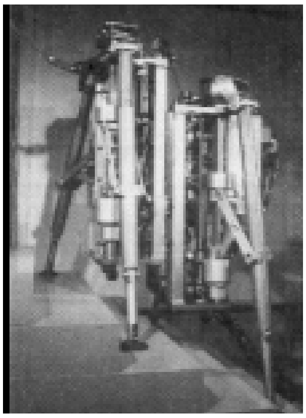

FIGURE 14. Titan VI by the Hirose & Yoneda Lab at The Tokyo Institute of Technology [H&Y].

Titan VI uses prismatic legs and could run on flat ground with a top speed of 1 m/s and go up stairs with a slope of up to 40 degrees, see figure 14. A more detailed description on the robot can be found in Hirose et al (1991a) and Yoneda et al (1994).

Titan VIII uses motors situated at the hip to actuate the knee joint, through cables and pulleys, and is capable of a max velocity of 0.9 m/s using a dynamic gait, see figure 15. This robot is commercially available at the laboratory, see [H&Y].

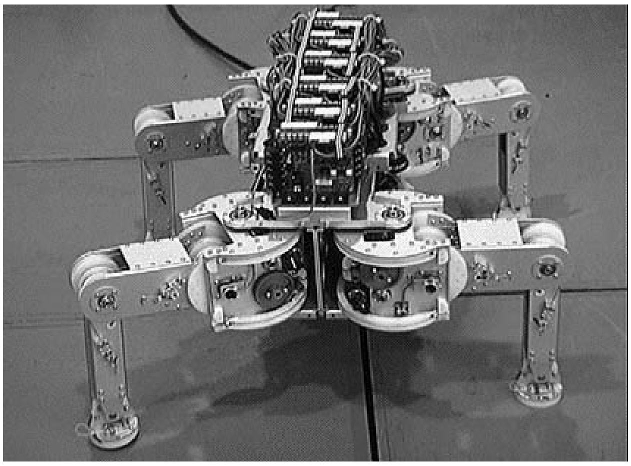

FIGURE 15. Titan VIII by the Hirose & Yoneda Lab at The Tokyo Institute of Technology [H&Y].

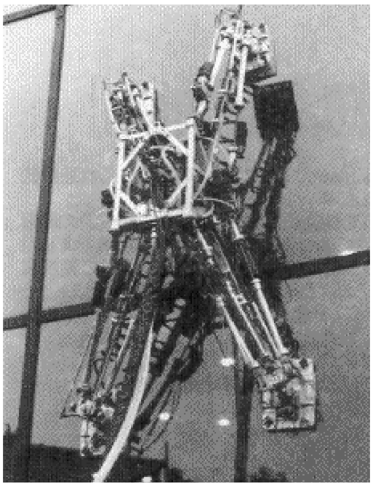

FIGURE 16. Ninja I by the Hirose & Yoneda Lab at The Tokyo Institute of Technology [H&Y].

Ninja I and II are wall climbing robots that use prismatic joints and suction pads on the feet to walk on walls and ceilings, see figure 16. A description of Ninja 1 and its gaits can be found in Hirose et al (1991b) and Nagakubo & Hirose (1994).

6.5 Bipeds

Biped robots can only balance by either using dynamic walk or feet that keep static stability.

6.5.1 The Leg Lab

The Leg Laboratory at Artificial Intelligence Laboratory, Massachusetts Institute of Technology, studies and builds dynamically balancing legged robots. The laboratory was founded in 1979 and initially they did research on a planar one-legged hopping machine under the supervision of Marc Raibert, to study control systems. They managed to build a series of one-, two- and four-legged hoppers, both planar and in 3-D, by expanding the relatively simple control system for the one-legged planar hopper. Raibert wrote a book on their experiments, Raibert (1986), that describes most of their earlier robots such as the planar and 3-D one legged hoppers and a quadruped.

The 3-D Biped was the last of the hopping machines developed, built 1992. It was capable of hopping on a flat plane and do tucked somersaults. A analysis of the gymnastic maneuvers and more information on the 3-D Biped can be found in Playter (1994).

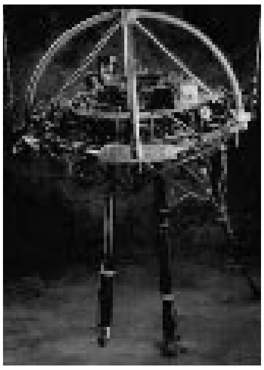

FIGURE 17. The 3-D Biped developed by MIT Leg Lab [MIT]

The Spring Turkey is a planar bipedal walking robot and one of the Lab’s current research projects. This robot was developed as an experimental platform for implementing force control actuation techniques, motion description and control techniques.

It has four degrees of freedom, an actuated hip and knee on each leg where each actuator is coupled in series with a spring to the joint. An unactuated boom constrains Spring Turkey's roll, yaw, and lateral motion thereby reducing it to a two dimensional robot. Spring Turkey weighs in at approximately 10 kg and stands 60 cm tall.

A description of their concepts and results are found in Pratt (1995), Pratt & Williamson (1995) and Pratt et al (1997)

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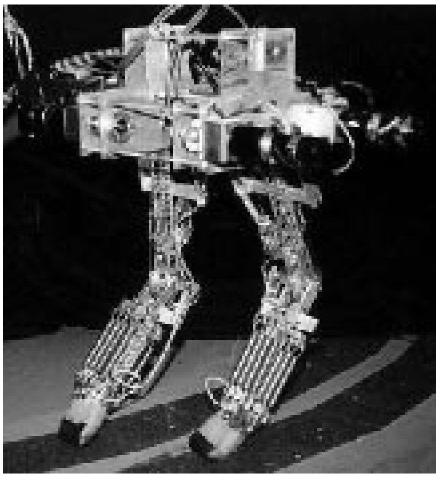

FIGURE 18. The Spring Turkey is a current research project at the Leg Lab, MIT [MIT].

6.5.2 Meltran II

At the Mechanical Engineering Laboratory (MEL) in Tsukuba, Japan, a biped robot, Meltran II, has been developed to walk over rugged terrain. A control scheme called the Linear Inverted Pendulum Mode is used to provide dynamic biped walking control. Meltran II can walk forward, walk backward and step in place. It’s equipped with a sonar on an arm that points out in front of the robot and senses the terrain at least two steps ahead which is crucial for control system to negotiate steps. The control of Meltran II is described in Kajita & Tani (1996) and more information can be found at MEL's homepage [MEL].

FIGURE 19. Meltran II by the Mechanical Engineering Laboratory, Tsukuba [MEL]

6.5.3 WL-12RVII

The Department of Mechanical Engineering and The Humanoid Research Laboratory, Advanced Research Center for Science and Engineering at Waseda University, Japan, has been studying biped walking since 1969. Takanishi et al (1985) describes briefly the history of their research. In 1972 it developed a eleven degrees of freedom hydraulically actuated biped robot that was the first in the world to accomplish automatic static biped walking by computer control. In 1983 a biped they developed walked with a quasi-dynamic gait, which is alternating static and dynamic in each step, the dynamic part occurring when the weight is shifted from one leg to the other. In 1985 they managed to build a dynamically walking biped robot.

Their current biped, WL-12RVII (Waseda Leg No. 12 Refined Version II), is capable of dynamic walking that adapts to the walking surface. It has nine degrees of freedom which are actuated by an electric hydraulic servo system combining a hydraulic rotating actuator with a servo valve. The total weight of the robot is 109 kg and its height is 1.87 m. It has an active, three degrees of freedom, trunk for compensating moments produced by walking, and a special foot for obtaining the position relative the walking surface and the gradient of the surface which is used by the adaptive controller. This robot is capable of walking at speeds up to 0.2 m/s. Its predecessor WL-12RVI that was without the special feet, was capable of walking at speeds up to 0.6 m/s on a flat ground. More information on the special foot is found in Yamaguchi et al (1995) and for experiments on the WL-12RVII in Yamaguchi et al (1996).

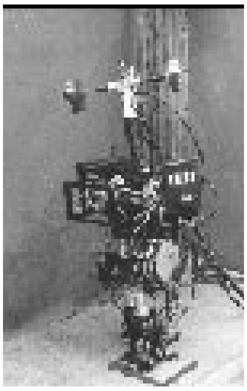

FIGURE 20. The WL-12RVI at Waseda University [WU]

7.0 Articulated Locomotion

Articulated locomotion is used by mobile robots that are composed of several articulated body segments linked linearly, giving them a train-like appearance. Locomotion can then be achieved by a variety of coordinated motion of the segments. Such locomotion has biological counterparts in the gaits of snakes, worms and slugs. They often use wheels, tracks or legs under each segment to reduce ground friction.

The advantages are

- The robots are hyper-redundant and have a very large degree of kinematic redundancy
- They can actively adapt it's body to the ground or between obstacles
- it can stiffen it's joints to pass over a ditch (reach over) or softening them to distribute weight when passing over marsh.
- redundancy in actuators gives them better reliability
- they can pass through narrow paths and tight corners

The disadvantage is

- large ground contact gives more friction
- the motion generation is complex

7.1 Koryu II

At the Hirose & Yoneda Laboratory, Tokyo Institute of Technology, an articulated robot Koryu II has been developed. It is composed of cylindrically shaped units having three degrees of freedom, a rotational motion that swings the segment, a translating motion which slides the segments up and down and in the wheel axis for propulsion. The segments are unitized so they are easily connected together or disconnected for transportation. More information can be found at the lab homepage [H&Y].

FIGURE 21. Koryu II by the Hirose & Yoneda Lab at The Tokyo Institute of Technology [H&Y].

8.0 Hybrids

Here a hybrid is a combination of two or more different types of locomotion systems. There are two types of vehicles. The first type switches between locomotion systems, depending on what kind of terrain it is travelling over or what kind of task it si performing, e.g. a vehicle equipped with tracks for fast locomotion, and legs for more difficult terrain. The second type is vehicles that combine features of different systems, e.g. a legged robot with driving wheels attached to the end of each leg, the legs provide active suspension and make it able to negotiate higher obstacles.

8.1 The MEL Hybrid

At Mechanical Engineering Laboratory (MEL) in Tsukuba, Japan, a hybrid locomotion system for an automated excavating robot has been studied. For this reason they are experimenting with a small robot that has four legs and a pair of tracks. The idea is that the excavator uses the tracks for relatively long distance travelling between working sites, and the legs are used for local movements while it is digging.

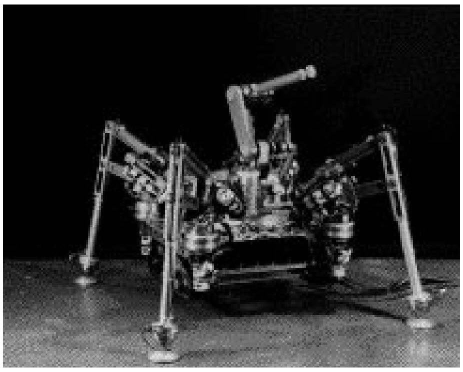

FIGURE 22. A hybrid developed at MEL [MEL].

9.0 Comparison and Conclusions

This survey of locomotion systems for difficult terrain has presented some different solutions that have been used in vehicles, especially mobile robots. The availible systems were diveded into wheeled, tracked, legged, articulated and hybrid systems. The advantages and disadvantages of each system was discussed and examples of vehicles were given. The general properties of terrain was discussed as the problem of choosing locomotion system depending on the functional and operational requirements of the robot.

In table 1, a comparison of the different concepts is shown. The parameters used for comparison are some that might be important for a vehicle in difficult terrain but this comparison should not be seen as a general evaluation of each locomotion system. As has been seen in the chapters above, there are a variety of different configurations for each type of system that would have to be evaluated individually. However to give an example on the general differences the following vehicles were chosen:

- wheeled: a normal four-wheel-drive jeep
- tracked: with a pair of tracks
- legged: a hexapod walking machine
- articulated: similar to Koryu II in section 7.1

Further, the size of the vehicles are assumed to be similar, or the size of a jeep.

TABLE 1. Comparison of locomotion systems

	Wheels	**Tracks**	**Legs**	**Articul.**
Soft ground	o	+	o	+
Rough ground	+	o	++	+
Speed	+	o	-	o
Agility	+	o	+	+
Stability	o	+	+	-
Adaptability	o	-	+	+
Complexity	+	+	-	-
Payload	+	+	-	o
Efficiency	+	o	-	-
Reliability	+	o	-	-
Fault tolerance	o	o	+	+
Environmental effects	o	-	+	o

According to table 1, wheeled locomotion has the highest ranking followed by the tracked vehicle. These are also the most used systems in vehicles today but this evaluation is in some aspects unfair. The evaluation of the parameters for the vehicles can be hard and in some cases unjust. As an example, legged and articulated vehicles were given a bad grade for reliability and effiecency. This is mainly due to that they are still in experimental stages.

Wheeled and tracked vehicles are well known systems and much has been written about them while legged are less known. It was felt that it could be of intrest to many to give legged robots a special attention in this survey. The field is also advancing rapidly and new robots are being introduced.

Acknowledgments

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[CMU]
Carnegie Mellon University, The Robotics Institute, USA.
[http://www.ri.cmu.ed:80ri-welcome.html/]

[CWRU]
Case Western Reserve University, The Autonomous Agents Research Group, USA
[http://yuggoth.ces.cwru.edu/]

[ISR]
IS Robotics, USA
[http://www.isr.com/]

[MIT]
Massachusetts Institute of Technology, Artificial Intelligence Laboratory, USA.
[http://www.ai.mit.edu/]

[MEL]
Mechanical Engineering Laboratory, Robotics, Tsukuba, Japan.
[http://www.aist.go.jp/MEL/enghome.html]

[MFEX]
The Microrover Flight Experiment

[PLU]
Plustech OY, Finland.
[http://www.plustech.fi/]

[H&Y]
Tokyo Institute of Technology, Hirose & Yoneda Laboratory, Japan
[http://mozu.mes.titech.ac.jp/]

[WU]
Waseda University, Humanoid Project, Group C:,Mechanism and Mind, Japan.
[http://www.shirai.info.waseda.ac.jp/humanoid/]