2 Locomotion

2.1 Introduction

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

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

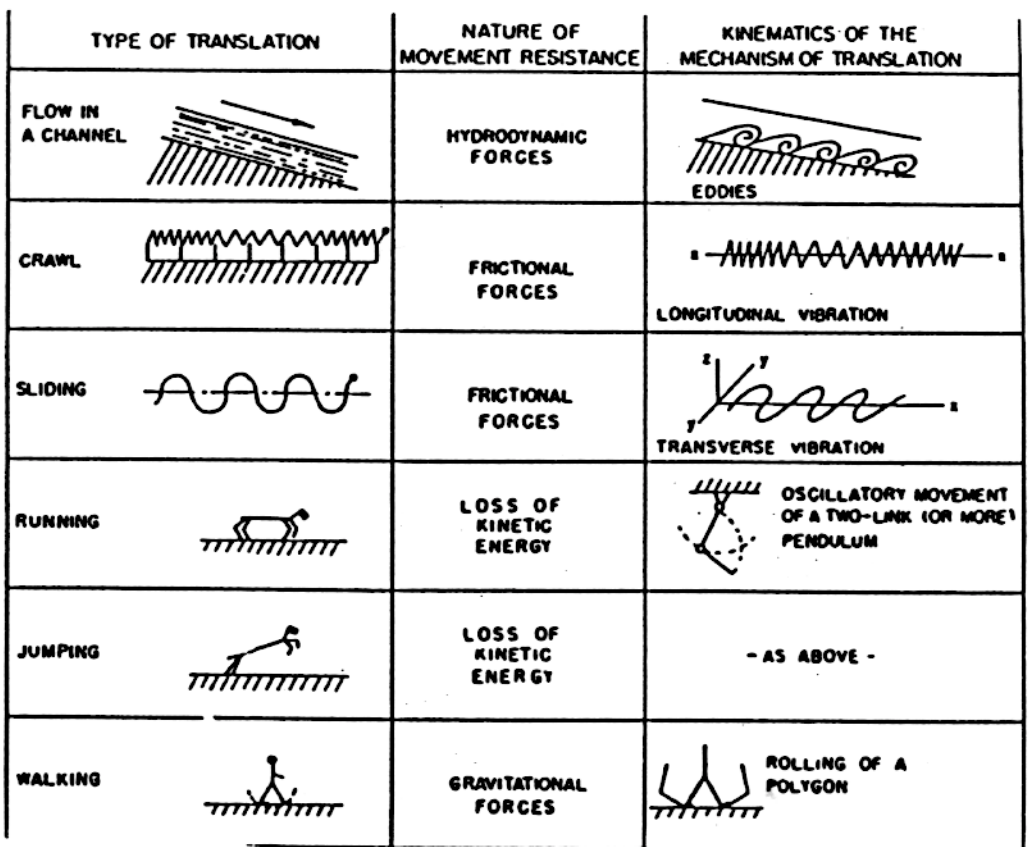


Fig 2.1 Locomotion mechanisms used in biological systems

Biological systems succeed in moving through a wide variety of harsh environments. Therefore it can be desirable to copy their selection of locomotion mechanisms. However, replicating nature in this regard is extremely difficult for several reasons. To begin with, mechanical complexity is easily achieved in biological systems through structural replica-

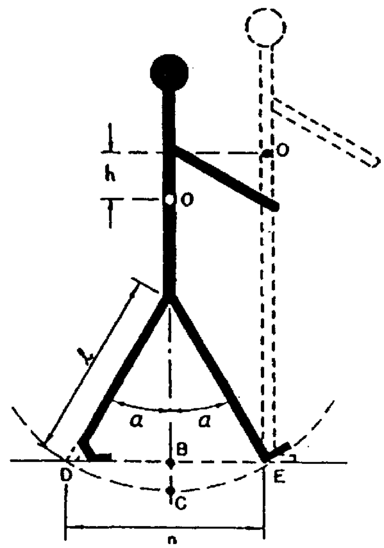


Fig 2.2 *Walking biped*

tion. Cell division, in combination with specialization, can readily produce a millipede with several hundred legs and several tens of thousands of individually sensed cilia. In man-made structures, each part must be fabricated individually, and so no such economies of scale exist. Additionally, the cell is a microscopic building block that enables extreme miniaturization. With very small size and weight, insects achieve a level of robustness that we have not been able to match with human fabrication techniques. Finally, the biological energy storage system and the muscular and hydraulic activation systems used in animals and insects achieve torque, response time and conversion efficiencies that far exceed similarly scaled man-made systems.

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

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

In effect, the efficiency of wheeled locomotion depends greatly on environmental qualities, particularly the flatness and hardness of the ground, while the efficiency of legged locomotion depends on the leg mass and body mass, both of which the robot must support at various points in a legged gait.

It is understandable therefore that nature favors legged locomotion, since locomotion systems in nature must operate on rough and unstructured terrain. For example, in the case of insects in a forest the vertical variation in ground height is often an order of magnitude great-

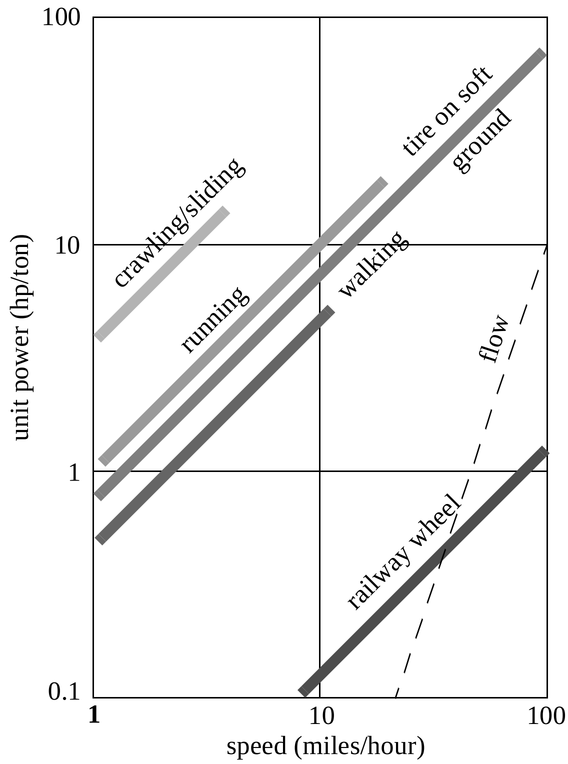


Fig 2.3 *Specific power versus attainable speed of various locomotion mechanisms* [32]

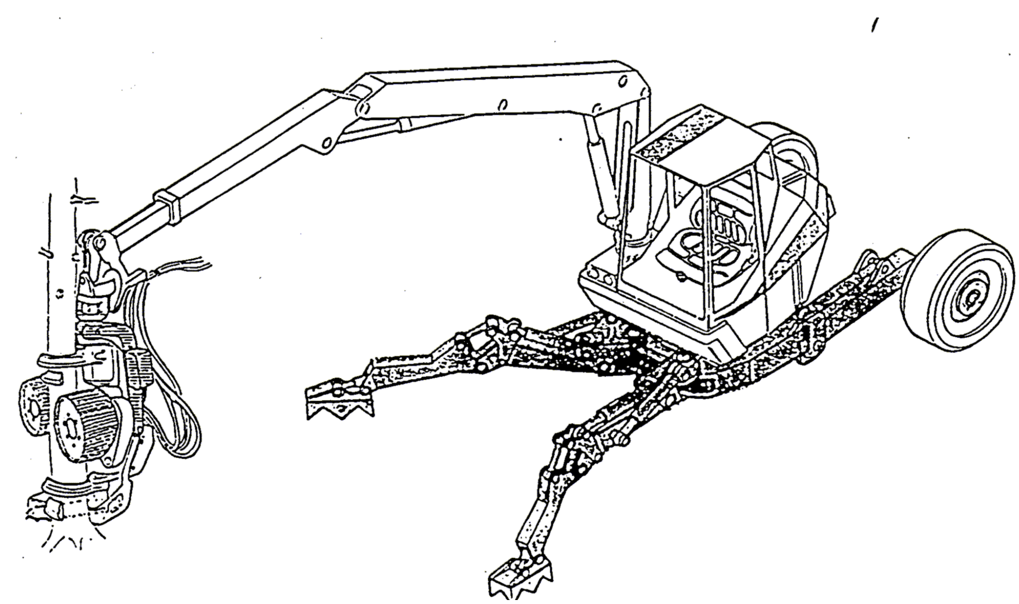


Fig 2.4 *RoboTrac, a hybrid wheel-leg vehicle for rough terrain*

er than the total height of the insect. By the same token, the human environment frequently consists of engineered, smooth surfaces both indoors and outdoors. Therefore, it is also understandable that virtually all industrial applications of mobile robotics utilize some form of wheeled locomotion. Recently, for more natural outdoor environments, there has been some progress toward hybrid and legged industrial robots such as the forestry robot shown in figure 2.4.

In the next section, we present general considerations that concern all forms of mobile robot locomotion. Following this will be overviews of legged locomotion and wheeled locomotion techniques for mobile robots.

Key issues for locomotion

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

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

A theoretical analysis of locomotion begins with mechanics and physics. From this starting point, we can formally define and analyze all manner of mobile robot locomotion systems. However, this book focuses on the mobile robot *navigation* problem, particularly stressing perception, localization and cognition. Thus we will not delve deeply into the physical basis of locomotion. Nevertheless, two remaining sections in this chapter present overviews of issues in legged locomotion [32] and wheeled locomotion. Then, Chapter 3 presents a more detailed analysis of the kinematics and control of wheeled mobile robots. More information is available from the internet links and bibliography in Chapter 7 (Roland, ensure this is the right reference. Is this for the bibliography in general?).

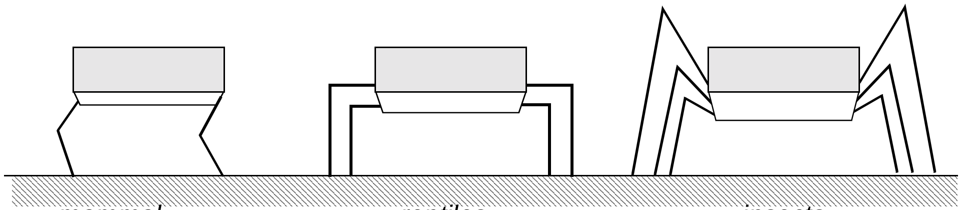


Fig 2.5 Arrangement of the legs of various animals

2.2 Legged Mobile Robots

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

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

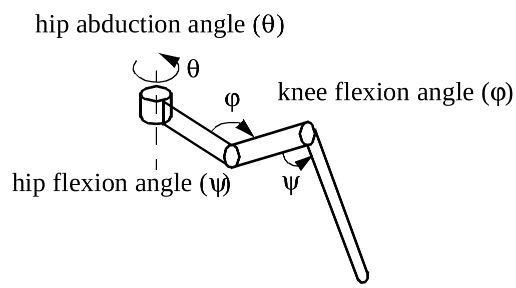
2.2.1 Leg configurations and stability

Because legged robots are biologically inspired, it is instructive to examine biologically successful legged systems. A number of different leg configurations have been successful in a variety or organisms (figure 2.5). Large animals such as mammals and reptiles have 4 legs whereas insects have 6 or more legs. In some mammals, the ability to walk on only two legs has been perfected. Especially in the case of humans, balance has progressed to the point that we can even jump with one leg[1]. This exceptional maneuverability comes at a price: much more complex active control to maintain balance.

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

But a robot must be able to lift its legs in order to walk. In order to achieve static walking, a robot must have at least 6 legs. In such a configuration, it is possible to design a gait in which a statically stable tripod of legs is in contact with the ground at all times (figure 2.8).

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



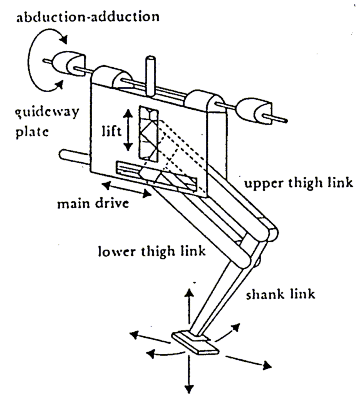


Fig 2.6 Two examples of legs with three degrees of freedom (DOF)

Insects are immediately able to walk when born (e.g. spiders). For them, the problem of balance during walking is relatively simple. Mammals, with four legs, cannot achieve static walking, but are able to stand easily on four legs. Fauns, for example, spend several minutes attempting to stand before they are able to do so, then spend several more minutes learning to walk without falling. Humans, with two legs, cannot even stand in one place with static stability. Infants require months to stand and walk, and even longer to learn to jump, run and stand on one leg.

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

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

In the case of legged mobile robots, a minimum of two degrees of freedom (DOF) is generally required to move a leg forward by lifting the left and swinging it forward. More common is the addition of a third DOF for more complex maneuvers, resulting in legs such as those shown in figure 2.6. Recent successes in the creation of bipedal walking robots have added a fourth DOF at the ankle joint. The ankle enables more consistent ground contact by actuating the pose of the sole of the foot.

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

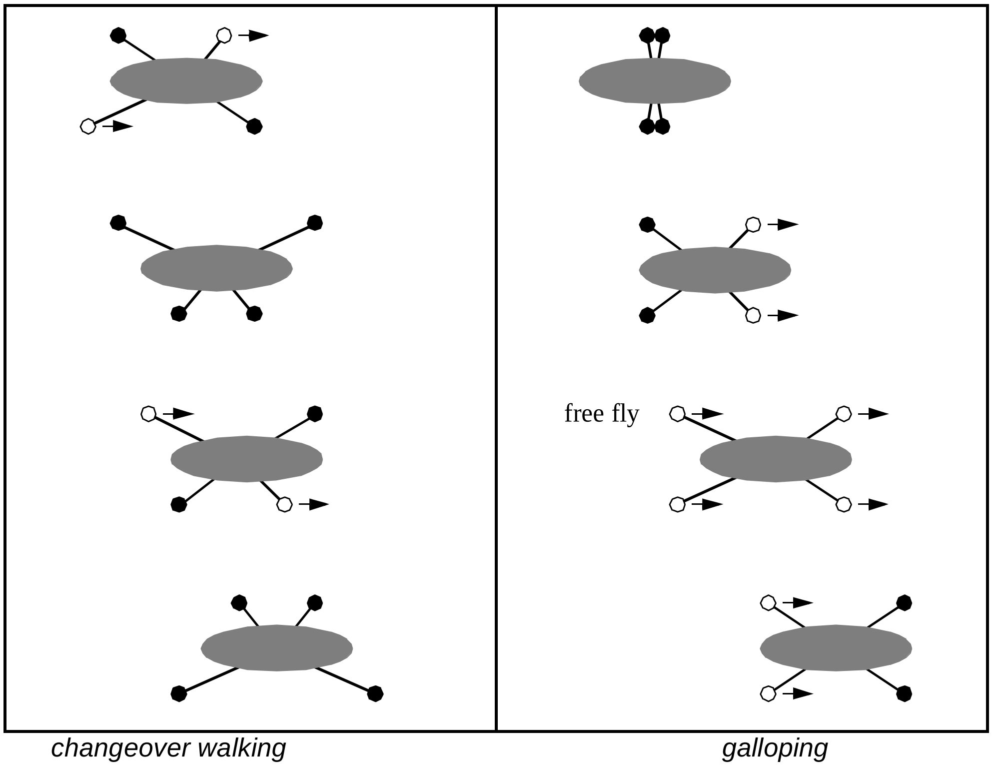


Fig 2.7 Two gaits with 4 legs. Because this robot has less than 6 legs, static walking is not generally possible.

ators.

In the case of a multi-legged mobile robot, there is the issue of leg coordination for locomotion, or gait control. The number of possible gaits depends on the number of legs [32]. The gait is a sequence of lift and release events for the individual legs. For a mobile robot with k legs, the total number of possible events N for a walking machine is

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

For a biped walker k=2 legs the number of possible events N is

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

The 6 different events are:

- lift right leg
- lift left leg
- release right leg
- release left leg
- lift both legs together
- release both legs together

Of course, this quickly grows quite large. For example, a robot with 6 legs has far more gaits theoretically:

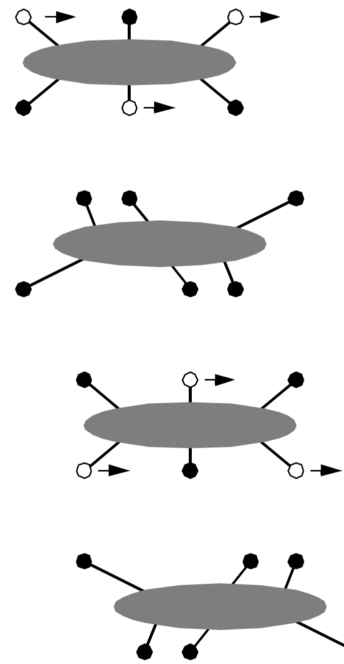


Fig 2.8 Static walking with 6 leg. A tripod formed by 3 legs always exists.

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

Figure 2.7 and 2.8 depict several four-legged gaits and the static 6-legged tripod gait.

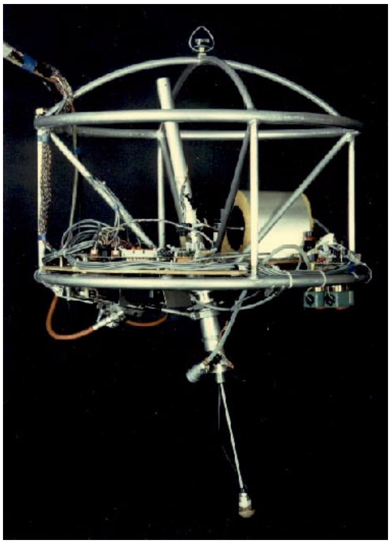
2.2.2 Examples of legged robot locomotion

Although there are no high-volume industrial applications to date, legged locomotion is an important area of long-term research. Several interesting designs are presented below, beginning with the one-legged robot and finishing with six-legged robots. For a very good overview of climbing and walking robots, see *http://www.uwe.ac.uk/clawar/*.

2.2.2.1 Single leg

The minimum number of legs a legged robot can have is, of course, one. Minimizing the number of legs is beneficial for several reasons. Body mass is particularly important to walking machines, and the single leg minimizes cumulative leg mass. Leg coordination is required when a robot has several legs, but with one leg no such coordination is needed. Perhaps most importantly, the one-legged robot maximizes the basic advantage of legged locomotion: legs have single points of contact with the ground in lieu of an entire track as with wheels. A single legged robot requires only a sequence of single contacts, making it amenable to the roughest terrain. Furthermore, a hopping robot can dynamically cross a gap that is larger than its stride by taking a running start, whereas a multi-legged walking robot that cannot run is limited to crossing gaps that are as large as its reach.

The major challenge of creating a single-leg robot is balance. For a robot with one leg, static walking is not only impossible, but static stability when stationary is also impossible. The robot must actively balance itself by either changing its center of gravity or by imparting



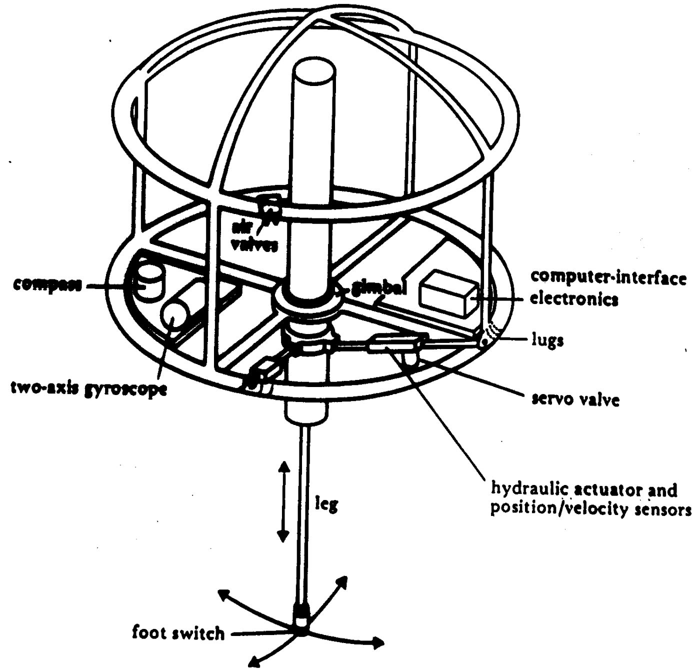


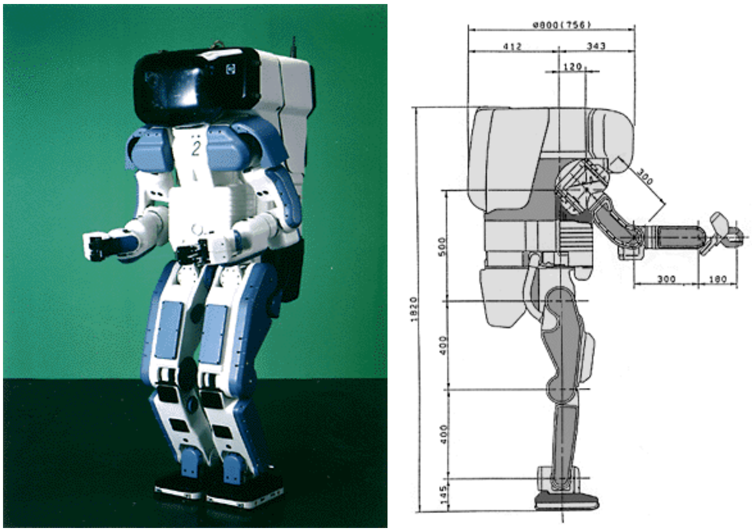
Fig 2.9 *The Raibert hopper [10,78]*

Fig 2.10 The 2D single Bow Leg Hopper [79]

corrective forces. Thus, the successful single-leg robot must be dynamically stable.

Figure 2.9 shows the Raibert Hopper [10, 78], one of the most well-known single-leg hopping robots created. This robot makes continuous corrections to body attitude and to robot velocity by adjusting the leg angle with respect to the body. The actuation is hydraulic, including high-power longitudinal extension of the leg during stance to hop back into the air. Although powerful, these actuators require a large, off-board hydraulic pump to be connected to the robot at all times.

Figure 2.10 shows a more energy efficient design developed more recently [79]. Instead of supplying power by means of an off-board hydraulic pump, the Bow Leg Hopper is designed to capture the kinetic energy of the robot as it lands using an efficient bow spring leg. This spring returns approximately 85% of the energy, meaning that stable hopping requires only the addition of 15% of the required energy on each hop. This robot, which is constrained



Specifications:

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

Fig 2.11 The humanoid robot P2 from Honda, Japan

along one axis by a boom, has demonstrated continuous hopping for 20 minutes using a single set of batteries carried on board the robot. As with the Raibert Hopper, the Bow Leg Hopper controls velocity by changing the angle of the leg to the body at the hip joint.

The paper of Ringrose [80] demonstrates the very important duality of mechanics and controls as applied to a single leg hopping machine. Often clever mechanical design can perform the same operations as complex active control circuitry. In this robot, the physical shape of the foot is exactly the right curve so that when the robot lands without being perfectly vertical, the proper corrective force is provided from the impact, making the robot vertical by the next landing. This robot is dynamically stable, and is furthermore passive. The correction is provided by physical interactions between the robot and its environment, with no computer nor any active control in the loop.

2.2.2.2 Two legs (biped)

A variety of successful bipedal robots have been demonstrated over the past ten years. Two-legged robots have been shown to run, jump, travel up and down stairs and even do aerial tricks such as somersaults. Figure 2.11 shows the Honda P2 bipedal robot, which is the product of tens of millions of research dollars and more than ten years of work. This biped can walk on slopes, climb and descend stairs, and push shopping carts. The crucial technology that enables this robot is Honda's research into the fabrication of extremely high torque, low mass motors that serve as the robot's joints. In the case of P2, the most significant obstacle that remains is energy capacity, efficiency and autonomous navigation. This robot can operate for only about 20 minutes with on-board power.

An important feature of bipedal robots is their anthropomorphic shape. They can be built to have the same approximate dimensions as humans, and this makes them excellent vehicles for research in human-robot interaction. Wabian is a robot built at Waseda University (figure 2.12) for just such research (Roland, see my reference in the notes.txt). Wabian is being designed to emulate human motion, and is even designed to dance like humans.

Specification:

Weight:107 kg
Height:1.66 m
DOF in total:43

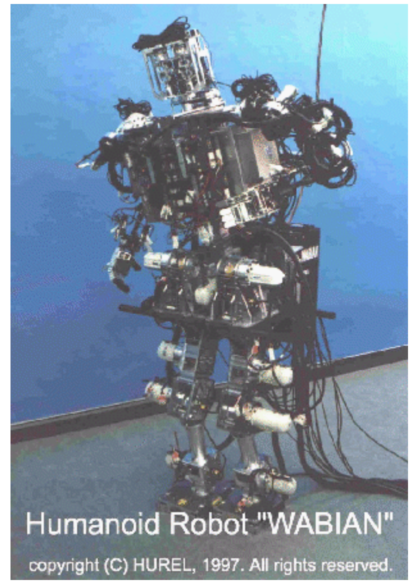


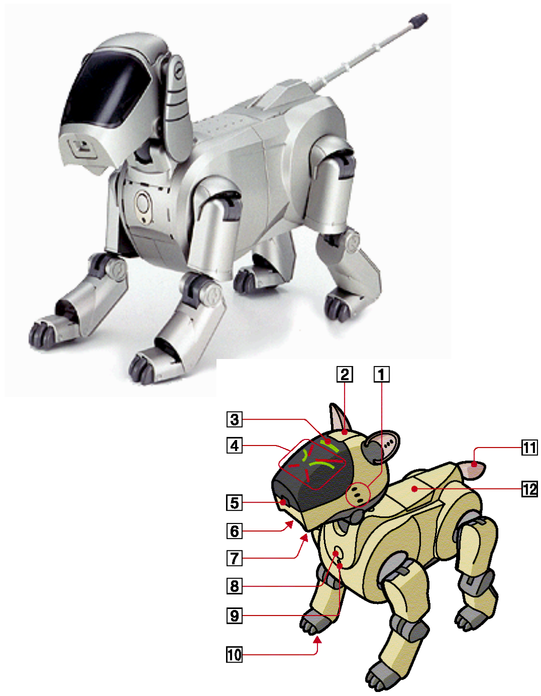
Fig 2.12 The humanoid robot WABIAN at Waseda University in Japan (Roland-ref)).

Fig 2.13 The Spring Flamingo developed at MIT [81]

Bipedal robots can only be statically stable within some limits, and so robots such as P2 and Wabian generally must perform continuous balance-correcting servoing even when standing still. Furthermore, each leg must have sufficient capacity to support the full weight of the robot. In the case of four-legged robots, the balance problem is facilitated along with the load requirements of each leg. An elegant design of a biped robot is the Spring Flamingo of MIT (figure 2.13). This robot inserts springs in series with the leg actuators to achieve a more elastic gait. Combined with "kneecaps" that limit knee joint angles, the Flamingo achieves surprisingly biomimetic motion.

2.2.2.3 Four legs (quadruped)

Although standing still on four legs is passively stable, walking remains challenging because to remain stable the robot's center of gravity must be actively shifted during the gait. Sony recently invested several million dollars to develop a four-legged robot (figure 2.14). To create this robot, Sony created both a new robot operating system that is near real-time and invented new geared servomotors that are sufficiently high torque to support the robot, yet backdriveable for safety. In addition to developing custom motors and software, Sony incor-



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

Fig 2.14 The artificial dog from Sony, Japan

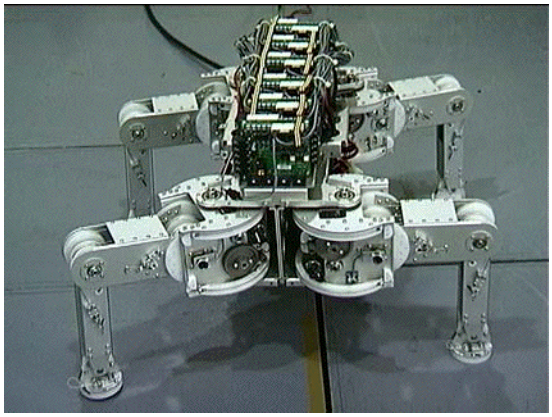
porated a color vision system that enables Aibo to chase a brightly colored ball. The robot is able to function for at most one hour before requiring recharging. Early sales of the robot have been very strong, with more than 60,000 units sold in the first year. Nevertheless, the number of motors and the technology investment behind this robot dog have resulted in a very high price of approximately $1500.

Four legged robots have the potential to serve as effective artifacts for research in human-robot interaction (fig. 2.15). Humans can treat the Sony robot, for example, as a pet and might develop an emotional relationship similar to that between man and dog. Furthermore, Sony has designed Aibo's walking style and general behavior to emulate learning and maturation, resulting in dynamic behavior over time that is more interesting for the owner who can track the changing behavior. As the challenges of high energy storage and motor technology are solved, it is likely that quadruped robots much more capable than Aibo will become common throughout the human environment.

2.2.2.4 Six legs (hexapod)

Six legged configurations have been extremely popular in mobile robotics because of their static stability during walking, thus reducing the control complexity (figure 2.16 and 2.17). In most cases, each leg has 3 DOF, including hip flexion, knee flexion and hip abduction (figure 2.6). Genghis is a commercially available hobby robot that has six legs, each of which has 2 DOF provided by hobby servos (figure 2.18). Such a robot, which consists only of hip flexion and hip abduction, has less maneuverability in rough terrain but performs quite well on flat ground. Because it consists of a straightforward arrangement of servo motors and straight legs, such robots can be readily built by a robot hobbyist.

Insects, which are arguably the most successful locomoting creatures on earth, excel at tra-



Specification:

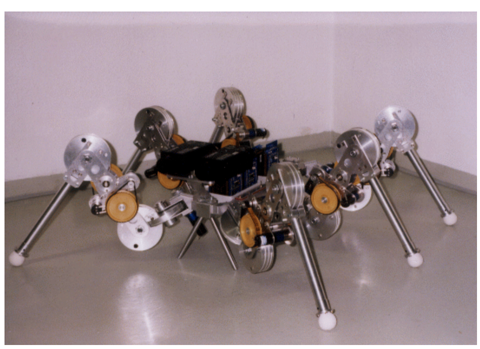
Weight:19 kg
Height:0.25 m
*DOF:4*3*

Fig 2.15 Titan VIII, a quadruped robot developed at Tokyo Institute of Technology http://mozu.mes.titech.ac.jp/research/walk/

Specification:

Maximum Speed:2.3 m/s
Weight:3.2 t
Height:3 m
Length:5.2 m
No. of legs:6
*DOF in total:6*3*

Fig 2.16 The human guided hexapod of Ohio State University



Specification:

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

Fig 2.17 Lauron II, a hexapod platform developed at University of Karlsruhe

versing all forms of terrain with six legs, even upside down. Currently, the gap between the capabilities of six-legged insects and artificial six-legged robots is still quite large. Interestingly, this is not due to a lack of sufficient numbers of degrees of freedom on the robots. Rather, insects combine a small number of active degrees of freedom with passive structures, such as microscopic barbs and textured pads, that increase the gripping strength of each leg significantly. Robotic research into such passive tip structures has only recently begun. For example, a research group is attempting to recreate the complete mechanical function of the cockroach leg (Roland, reference in notes (Espenschied et al.)).

It is clear from all of the above examples that legged robots have much progress to make before they are competitive with their biological equivalents. Nevertheless, significant gains

Fig 2.18 Genghis, one of the most famous walking robots from MIT uses hobby servomotors as its actuators *(http://www.ai.mit.edu/projects/genghis)*

have been realized recently, primarily due to advances in motor design. Creating actuation systems that approach the efficiency of animal muscle remains far from the reach of robotics, as does energy storage with the energy densities found in organic life forms.

2.3 Wheeled Mobile Robots

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

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

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

2.3.1 Wheeled locomotion: the design space

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

Wheel design

There are four major wheel classes, as shown in figure 2.19. They differ widely in their kinematics, and therefore the choice of wheel type has a large effect on the overall kinematics of the mobile robot. The standard wheel and the castor wheel have a primary axis of rotation and are thus highly directional. To move in a different direction, the wheel must be steered first along a vertical axis. The key difference between these two wheels is that the standard wheel can accomplish this steering motion with no side effects, as the center of rotation passes through the contact patch with the ground, while the castor wheel rotates around an offset axis, causing a force to be imparted to the robot chassis during steering.

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

The spherical wheel is a truly omnidirectional wheel, often designed so that it may be ac-

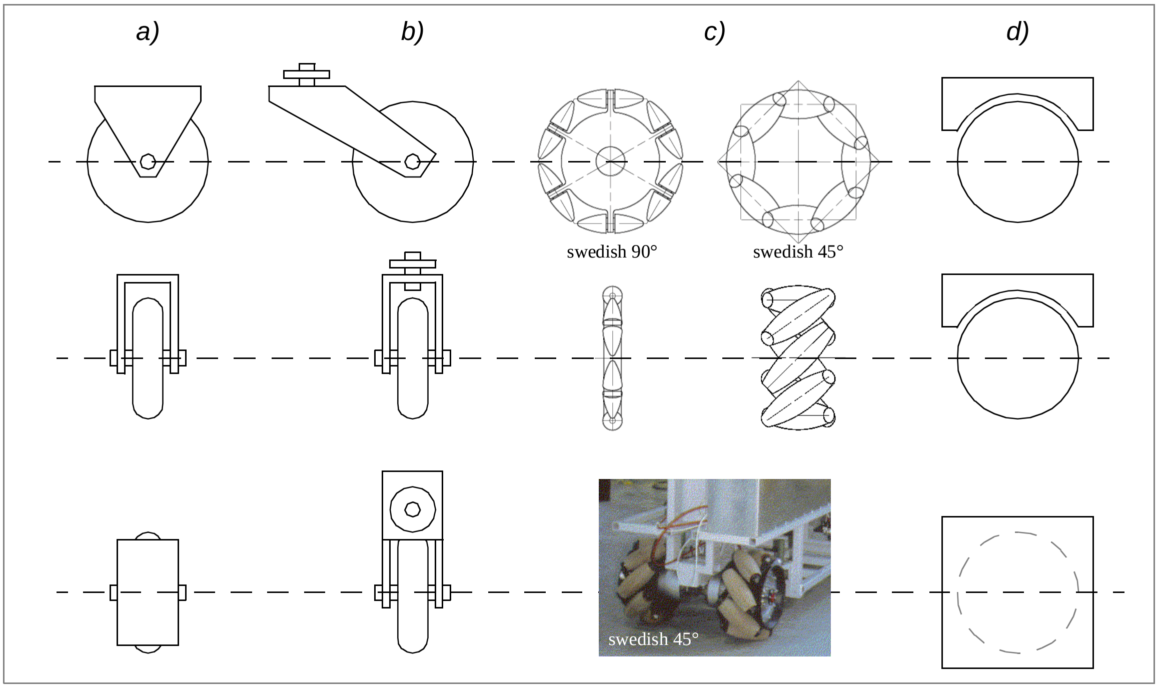


Fig 2.19 The four basic wheel types
a)Standard wheel: Two degrees of freedom; rotation around the (motorized) wheel axle and the contact point
b)castor wheel: Two degrees of freedom; rotation around an offset steering joint
c)Swedish wheel: Three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers and around the contact point

tively powered to spin along any direction. One mechanism for implementing this spherical design imitates the computer mouse, providing actively powered rollers that rest against the top surface of the sphere and impart rotational force.

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

Wheel geometry

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

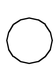
Unlike automobiles, which are largely designed for a highly standardized environment (the

Fig 2.20 Navlab I, the first autonomous highway vehicle that steers and controls the throttle using vision and radar sensors (ROLAND-ref in notes).

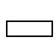
road network), mobile robots are designed for applications in a wide variety of situations. Automobiles all share similar wheel configurations because there is one region in the design space that maximizes maneuverability, controllability and stability for their standard environment: the paved roadway. However, there is no single wheel configuration that maximizes these qualities for the variety of environments faced by different mobile robots. So, you will see great variety in the wheel configurations of mobile robots. In fact, few robots use the Ackerman wheel configuration of the automobile because of its poor maneuverability, with the exception of mobile robots designed for the road system (figure 2.20).

Table 2.1 gives an overview of wheel configurations ordered by the number of wheels. This table shows both the selection of particular wheel types and their geometric configuration on the robot chassis. Note that some of the configurations shown are of little use in mobile robot applications. For instance, the 2-wheeled bicycle arrangement has moderate maneuverability and poor controllability. Like a single-leg hopping machine, it can never stand still. Nevertheless, this table provides an indication of the large variety of wheel configurations that are possible in mobile robot design.

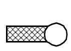
Icons for the each wheel type are as follows:

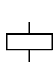
 unpowered omnidirectional wheel (spheric, castor, swedish)

 motorized swedish wheel (Stanford wheel)

 unpowered standard wheel

 motorized standard wheel

 motorized and steered castor wheel

 steered standard wheel

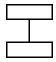
 connected wheels

Table 2.1: Wheel configurations for rolling vehicles

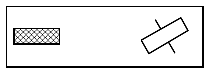
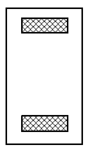
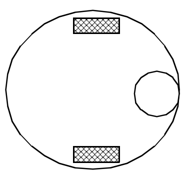
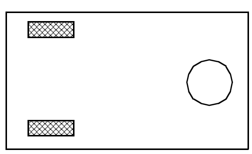
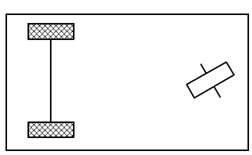
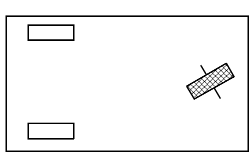
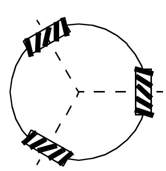
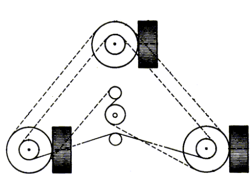
number of wheels	Arrangement	Description	Typical examples
2		One steering wheel in the front, one traction wheel in the rear	bicycle, motorcycle
		Two-wheel differential drive with the COM below the axle	Cye personal robot
3		Two-wheel centered differential drive with a third point of contact	Nomad Scout, smartRobII EPFL
		Two independently driven wheels in the rear/front, one unpowered omnidirectional wheel in the front/rear	many indoor robots, including the EPFL robots Pygmalion and Alice
		Two connected traction wheels (differential) in rear, one steered free wheel in front	Piaggio mini-trucks
		Two free wheels in rear, one steered traction wheel in front	Neptune (Carnegie-Mellon University, Hero-1
		3 motorized swedish or spheric wheels arranged in a triangle. Omnidirectional movement is possible.	Stanford-wheel Tribolo EPFL, Palm Pilot Robot Kit
		3 synchronously motorized and steered wheels. The orientation is not controllable.	‘synchro drive’ Denning MRV-2, Georgia Institute of Technology, I-Robot B24, Nomad 200

Table 2.1: Wheel configurations for rolling vehicles

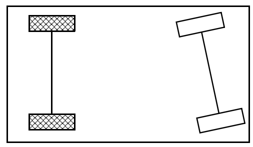
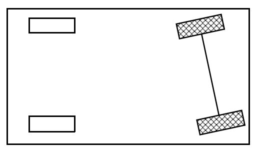
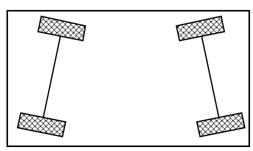
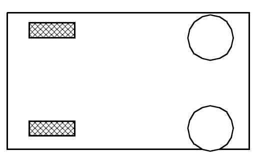
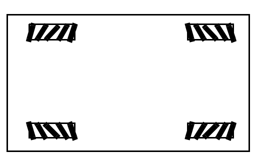
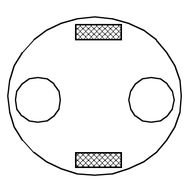
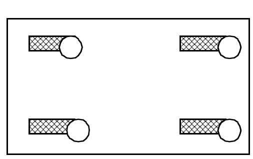
number of wheels	Arrangement	Description	Typical examples
4		2 motorized wheels in the rear, 2 steered wheels in the front; Steering has to be different for the two wheels to avoid slipping/ skidding.	car with rear wheel drive
		2 motorized and steered wheels in the front, 2 free wheels in the rear; Steering has to be different for the two wheels to avoid slipping/skidding.	car with front wheel drive
		4 steered and motorized wheels	four wheel drive, four wheel steering
		Two traction wheels (differential) in rear/front, two omnidirectional wheels in the front/rear	Charlie (DMT-EPFL)
		Four omnidirectional wheel	CMU Uranus
		Two wheel differential drive with two additional points of contact	EPFL Khepera, Hyperbot Chip
		Four motorized and steered castor wheels	Nomadic XR4000

Table 2.1: Wheel configurations for rolling vehicles

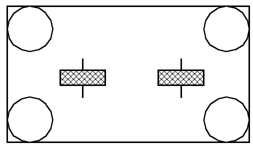
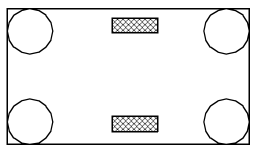
number of wheels	Arrangement	Description	Typical examples
6		Two motorized and steered wheels aligned in center, one omnidirectional wheel at each corner	First
		Two traction wheels (differential) in center, one omnidirectional wheel at each corner	Terregator (Carnegie Mellon University)

Fig 2.21 Cye, a commercially available domestic robot that can vacuum and make deliveries in the home, is built by Probotics, Inc.

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

Stability

Surprisingly, the minimum number of wheels required for static stability is two. As shown above, a two-wheel differential drive robot can achieve static stability if the center of mass is below the wheel axle. Cye is a commercial mobile robot that uses this wheel configuration (figure 2.21).

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

Maneuverability

Some robots are omnidirectional, meaning that they can move at any time in any direction along the ground plane (X,Y) regardless of the orientation of the robot around its vertical axis. This level of maneuverability requires wheels that can move in more than just a single direction, and so omnidirectional robots usually employ swedish or spherical wheels that are powered. A good example is Uranus, shown in figure 2.24. This robot uses four swedish wheels to rotate and translate independently and without constraints.

In general, the ground clearance of robots with swedish and spherical wheels is somewhat limited, due to the mechanical constraints of constructing omnidirectional wheels. An interesting recent solution to the problem of omnidirectional navigation while solving this ground clearance problem is the four castor-wheeled configuration in which each castor wheel is actively steered and actively translated. In this configuration, the robot is truly omnidirectional because, even if the castor wheels are facing a direction perpendicular to the desired direction of travel, the robot can still move in the desired direction by steering these wheels. Because the vertical axis is offset from the ground contact path, the result of this steering motion is robot motion.

In the research community, another classes of mobile robots are popular which achieve high maneuverability, only slightly inferior to that of the omnidirectional configurations. In such robots, motion in a particular direction may initially require a rotational motion. With a circular chassis and an axis of rotation at the center of the robot, such a robot can spin without changing its ground footprint. The most popular such robot is the two-wheel differential drive robot where the two wheels rotate around the center point of the robot. One or two additional ground contact points may be used for stability, based on the application specifics.

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

Controllability

There is generally an inverse correlation between controllability and maneuverability. For example, the omnidirectional designs such as the four castor-wheeled configuration require significant processing to convert desired rotational and translational velocities to individual wheel commands. Furthermore, such omnidirectional designs often have greater degrees of freedom at the wheel. For instance, the swedish wheel has a set of free rollers along the

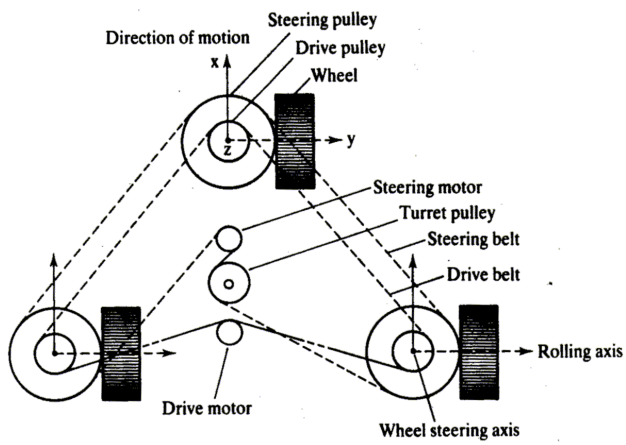


Fig 2.22 *Synchro Drive: The robot can move in any direction; however, the orientation of the chassis is not controllable.*

wheel perimeter. These degrees of freedom cause an accumulation of slippage, tend to reduce dead-reckoning accuracy and increase the design complexity.

Controlling an omnidirectional robot for a specific direction of travel is also more difficult and often less accurate when compared to less maneuverable designs. For example, an Ackerman steering vehicle can go straight simply by locking the steerable wheels and driving the drive wheels. In a differential drive vehicle, the two motors attached to the two wheels must be driven along exactly the same velocity profile, which can be challenging considering variations between wheels, motors and environmental differences. With four-wheel omnidrive, such as the Uranus robot which has four swedish wheels, the problem is even harder because all four wheels must be driven at exactly the same speed for the robot to travel in a perfectly straight line.

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

2.3.2 Wheeled locomotion: case studies

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

2.3.2.1 Synchro Drive

The synchro drive configuration (figure 2.22) is a popular arrangement of wheels in indoor mobile robot applications. It is an interesting configuration because, although there are three driven and steered wheels, only two motors are used in total. The one translation motor sets the speed of all three wheels together, and the one steering motor spins all the wheels together about each of their individual vertical steering axes. But note that the wheels are being steered with respect to the robot chassis, and therefore there is no direct way of re-orienting the robot chassis. In fact, the chassis orientation does drift over time due to uneven tire slippage, causing rotational dead-reckoning error.

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

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

2.3.2.2 Omnidirectional Drive

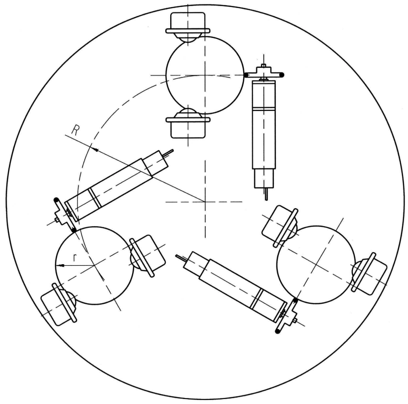
As we will see later in chapter 3.4.2, omnidirectional movement is be of great interest for complete maneuverability. Omnidirectional robots that are able to move in any direction $(, y, \theta)$ at any time are also holonomic (see chapter 3.4.2). They can be realized by either using spheric, castor or swedish wheels. Three examples of such holonomic robots are presented below.

Omnidirectional locomotion with three spheric wheels

The omnidirectional robot depicted in figure 2.23 is based on three spheric wheels, each actuated by one motor. In this design, the spheric wheels are suspended by three contact points, two given by spherical bearings and one by the a wheel connected to the motor axle. This concept provides excellent maneuverability and is simple in design. However, it is limited to flat surfaces and small loads, and it is quite difficult to find round wheels with high friction coefficients.

Omnidirectional locomotion with four swedish wheels

The omnidirectional arrangement depicted in figure 2.24 has been used successfully on several research robots, including the CMU Uranus. This configuration consists of four swedish 45 degree wheels, each driven by a separate motor. By varying the direction of rotation and relative speeds of the four wheels, the robot can be moved along any trajectory in the plane



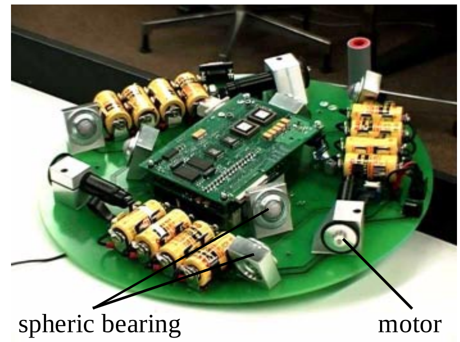


Fig 2.23 The Tribolo designed at EPFL, Switzerland
- Left: arrangement of spheric bearings and motors (bottom view)
- Right: Picture of the robot without the spheric wheels (bottom view)

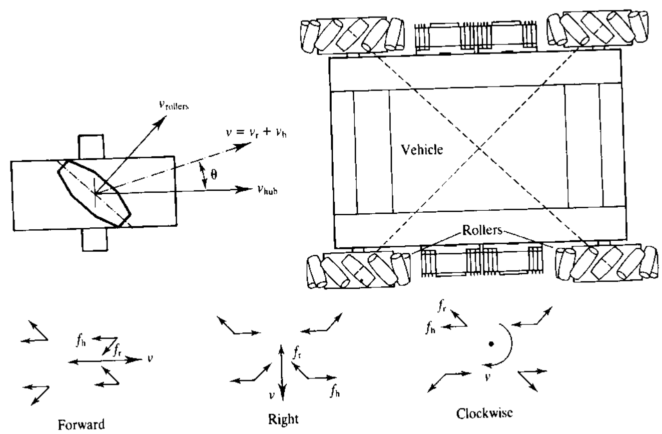


Fig 2.24 The Carnegie Mellon Uranus robot, an omnidirectional robot with four powered swedish 45 wheels.

and, even more impressively, can simultaneously spin around its vertical axis.

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

This four-wheel arrangement of swedish wheels is not minimal in terms of control motors. Because there are only 3 degrees of freedom in the plane, one can build a three-wheeled omnidirectional robot chassis using three swedish 90 degree wheels as shown in Table 2.1. However, existing examples such as Uranus have been designed with four wheels due to capacity and stability considerations.

One application for which such omnidirectional designs are particular amenable is mobile manipulation. In this case, it is desirable to reduce the degrees of freedom of the manipulator arm to save arm mass by using the mobile robot chassis motion for gross motion. As with humans, it would be ideal if the base could move omnidirectionally without greatly impact-

Fig 2.25 *The Nomad XR4000 from Nomadics Technology had an arrangement of 4 castor wheels for holonomic motion. All the castor wheels are driven and steered, thus requiring a precise synchronization and coordination to obtain a precise movement in , y and θ.*

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

Omnidirectional locomotion with four castor wheels and eight motors

Another solution for omnidirectionality is to use castor wheels. This is done for the Nomad XR4000 form Nomadics (fig. 2.25) giving it an excellent maneuverability. Unfortunately Nomadics Technology has ceased the production of mobile robots.

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

2.3.2.3 Tracked slip/skid locomotion

In the wheel configurations discussed above, we have made the assumption that wheels are not allowed to skid against the surface. An alternative form of steering, termed slip/skid, may be used to re-orient the robot by spinning wheels that are facing the same direction at different speeds or in opposite directions. The army tank operates this way, and Nanokhod, pictured below (figure 2.26) is an example of a mobile robot based on the same concept.

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

The disadvantage of such configurations is coupled to the slip/skid steering. Because of the large amount of skidding during a turn, the exact center of rotation of the robot is hard to predict and the exact change in position and orientation is also subject to variations depending on the ground friction. Therefore, dead-reckoning on such robots is highly inaccurate. This is the trade-off that is made in return for extremely good maneuverability and traction over rough and loose terrain. Furthermore, a slip/skid approach on a high-friction surface

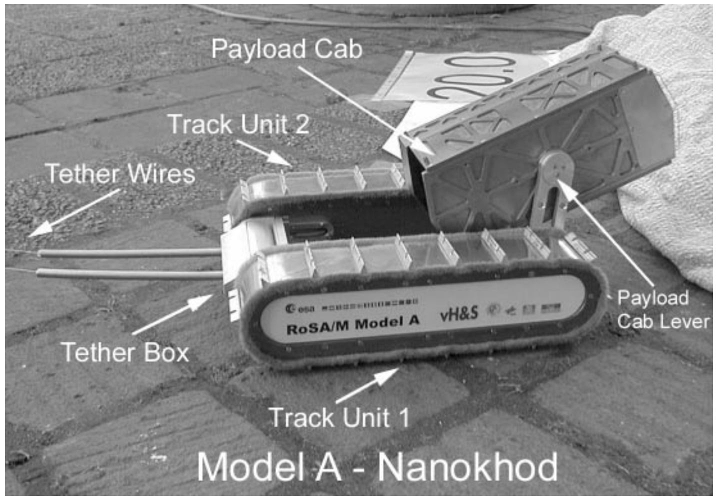


Fig 2.26 *The micro-rover NANOKHOD II, developed by von Hoerner & Sulger GmbH and Max Planck Institute, Mainz for European Space Agency (ESA) will probably go to Mars [ROLAND REF. in notes!]*

can quickly overcome the torque capabilities of the motors being used. In terms of power efficiency, this approach is reasonably efficient on loose terrain but extremely inefficient otherwise.

2.3.2.4 Walking Wheels

Walking robots might offer the best maneuverability in rough terrain. However, they are inefficient on flat ground and need sophisticated control. Hybrid solutions, combining the adaptability of legs with the efficiency of wheels offer an interesting compromise. Solutions that passively adapt to the terrain are of particular interest for field and space robotics. The Sojourner robot of NASA/JPL (fig. 1.2) represents such a hybrid solution, able to overcome objects up to the size of the wheels. A more advanced mobile robot design for similar applications has recently been produced by EPFL (fig. 2.27). This robot, called Shrimp[2], has 6 motorized wheels and is capable of climbing objects up to two times its wheel diameter [84,85]. This enables it to climb regular stairs though the robot is even smaller than the Sojourner. Using a rhombus configuration, the Shrimp has a steering wheel in the front and the rear, and two wheels arranged on a bogy on each side. The front wheel has a spring suspension to guarantee optimal ground contact of all wheels at any time. The steering of the rover is realized by synchronizing the steering of the front and rear wheels and the speed difference of the bogy wheels. This allows for high precision maneuvers and turning on the spot with minimum slip/skid of the four center wheels. The use of parallel articulations for the front wheel and the bogies creates a virtual center of rotation at the level of the wheel axis. This ensures maximum stability and climbing abilities even for very low friction coefficients between the wheel and the ground.

As mobile robotics research matures we find ourselves able to design more intricate mechanical systems. At the same time, the control problems of inverse kinematics and dynam-

2. *Patent pending*

Fig 2.27 *Shrimp, an all-terrain robot with outstanding passive climbing abilities (EPFL [84,85])*

ics are now so readily conquered that these complex mechanics can in general be controlled. So, in the near future, you should expect to see a great number of unique, hybrid mobile robots that draw together advantages from several of the underlying locomotion mechanisms that we have discussed in this chapter. They will each be technologically impressive, and each will be designed as the expert robot for its particular environmental niche.