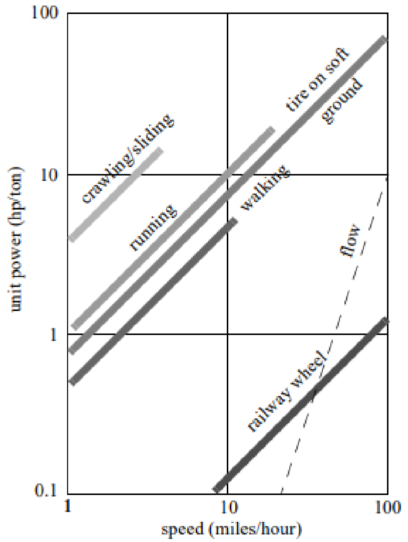
Professional Elective

Mobile Robots and Automated Guided Vehicles

INTRODUCTION

- 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



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

INTRODUCTION

- 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 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.

Legged Mobile Robots

- Legged robot 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 by way of its dexterous front legs.

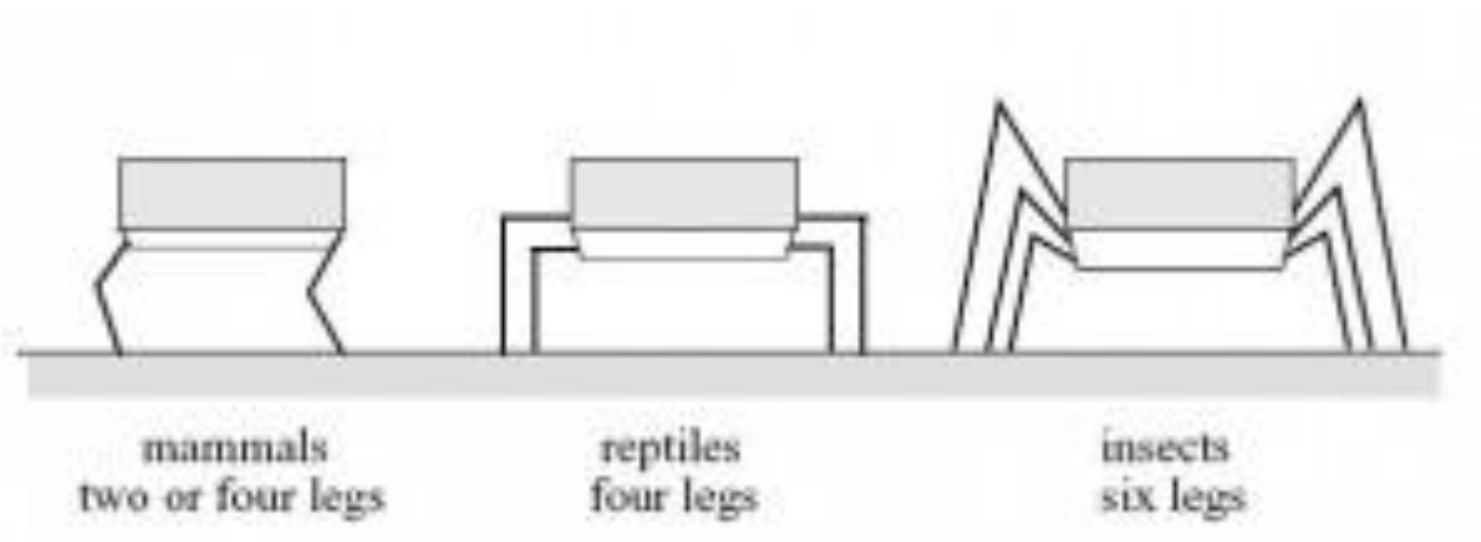
Legged Mobile Robots

- 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.

Leg configurations and Leg 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 of organisms.
- Large animals, such as mammals and reptiles, have four legs, whereas insects have six 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 leg1.
- This exceptional maneuverability comes at a price: much more complex active control to maintain balance.

Legged Mobile Robots



Arrangement of the legs of various animals.

Leg configurations and Leg stability

- 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 is passively corrected toward the stable pose when the upsetting force stops.

Leg configurations and Leg stability

- 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 six 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 Insects and spiders are immediately able to walk when born.
- 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.

Static Walking ; The centre of gravity of the robot is always within the area bounded by the feet that are touching the ground

The centre of gravity of the robot is always within the area bounded by the feet that are touching the ground Dynamic Walking Dynamic Walking At significant periods

The faun is a half-human and half-goat mythological creature appearing in Greek and Roman mythology.

Leg configurations and Leg stability

- 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 toward 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.

Leg configurations and Leg stability

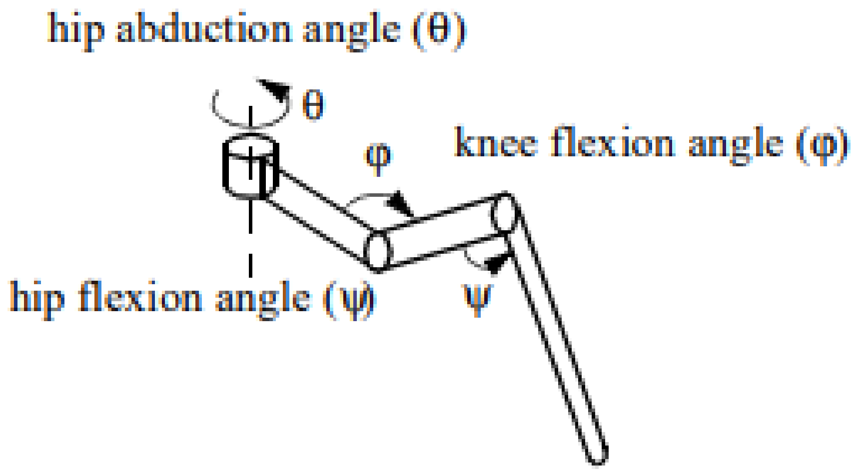
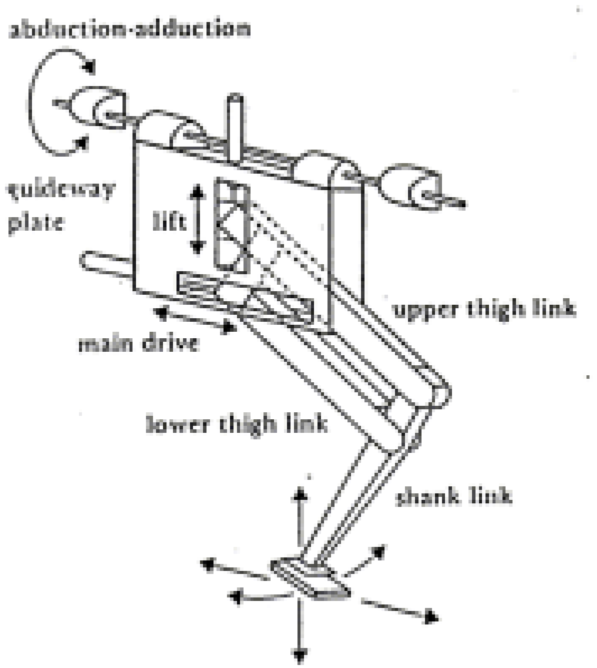


Fig 2.6 *Two examples of legs with three degrees of freedom (DOF)*



Two examples of legs with three degrees of freedom.

Types of legged Robots

- **One leg Robot:** 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 multilegged walking robot that cannot run is limited to crossing gaps that are as large as its reach.

one leg robot

Single leg

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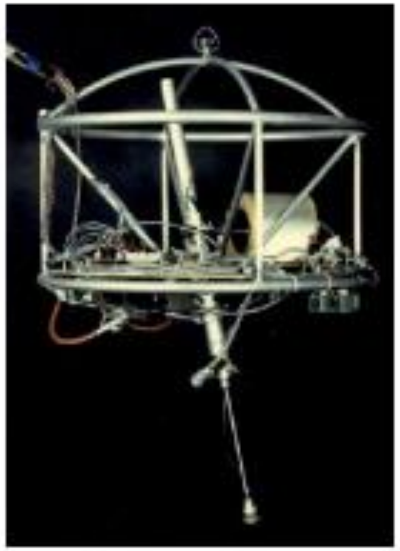
Single leg

- 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 centre of gravity or by imparting 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.

Single leg

- 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 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.



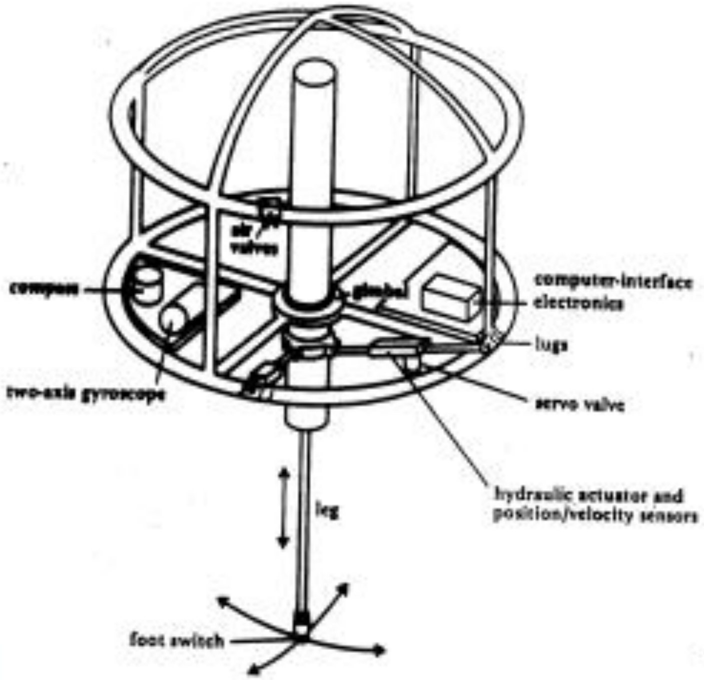
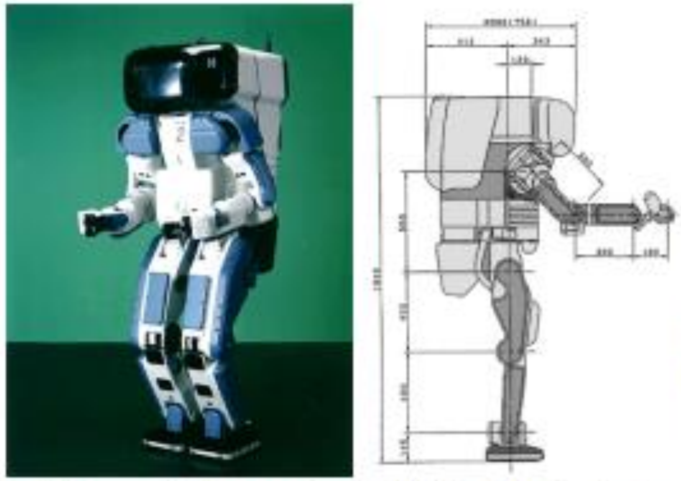


Fig 2.9 *The Raibert hopper [10,78]*

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



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*

Types of legged Robots

- **Two Leg Robot (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 stairways, and even do aerial tricks such as somersaults.
- In the commercial sector, both Honda and Sony have made significant advances over the past decade that have enabled highly capable bipedal robots.
- Both companies designed small, powered joints that achieve power-to-weight performance unheard of in commercially available servomotors.
- These new “intelligent” servos provide not only strong actuation but also compliant actuation by means of torque sensing and closed-loop control.

two leg robot

Two Leg Robot (biped):

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- 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.
- 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.

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]

Four legs (quadruped) Robot

- **Four legs (quadruped) Robot :** 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 locomotion.
- Four-legged robots have the potential to serve as effective artifacts for research in human-robot interaction.
- 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.

four leg robot

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 back driveable for safety.
- In addition to developing custom motors and software, Sony incorporated 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.

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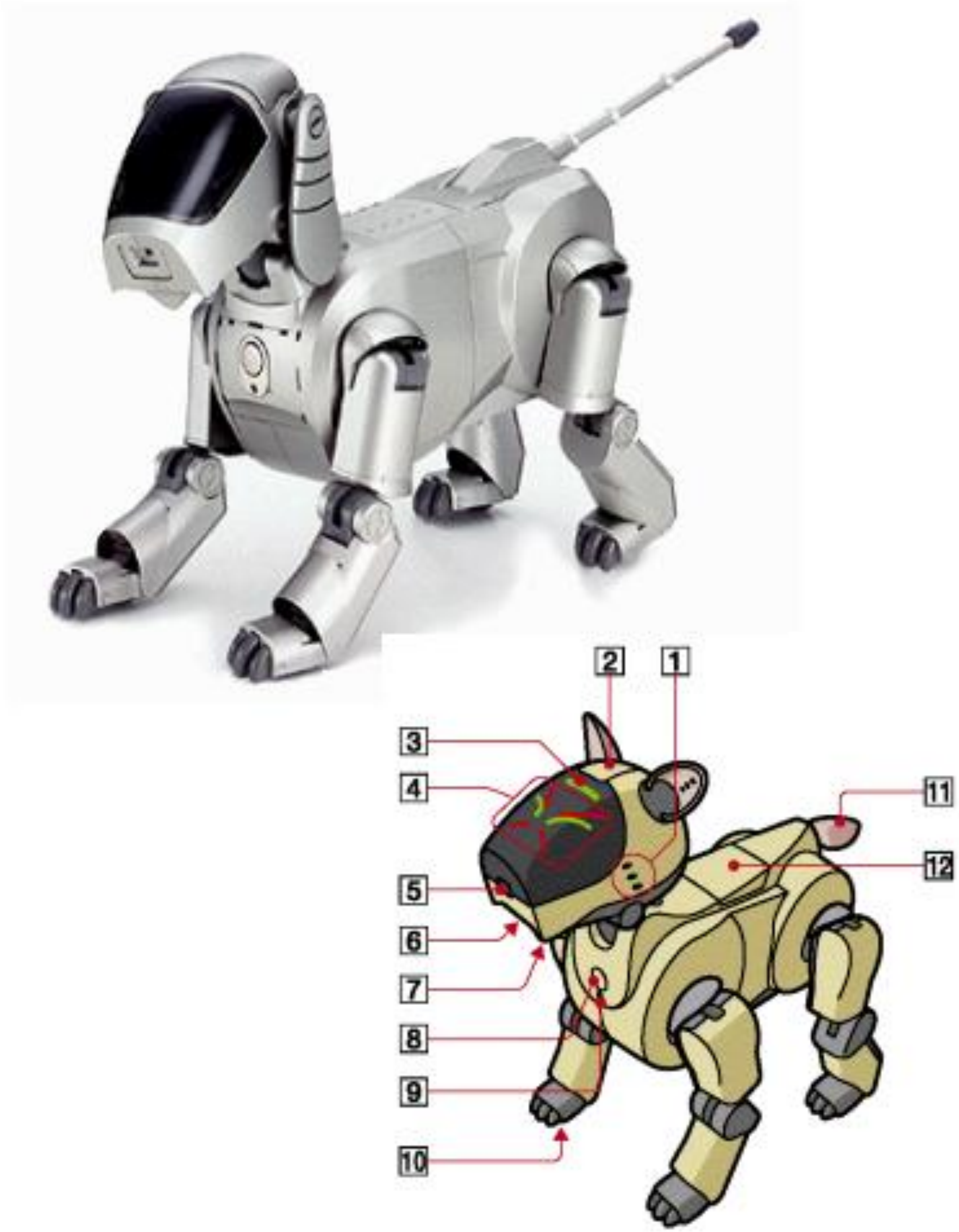

1 *Stereo microphone*
Allows AIBO to pick up surrounding sounds.
2 *Head sensor*
Senses when a person taps or pets AIBO on the head.
3 *Mode indicator*
Shows AIBO's operation mode.
4 *Eye lights*
These light up in blue-green or red to indicate AIBO's emotional state.
5 *Color camera*
Allows AIBO to search 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*

Six legs (hexapod) robot

- Six-legged configurations have been extremely popular in mobile robotics because of their static stability during walking, thus reducing the control complexity.
- Insects, which are arguably the most successful locomoting creatures on earth, excel at traversing 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.

Six legs (hexapod) robot

- 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.

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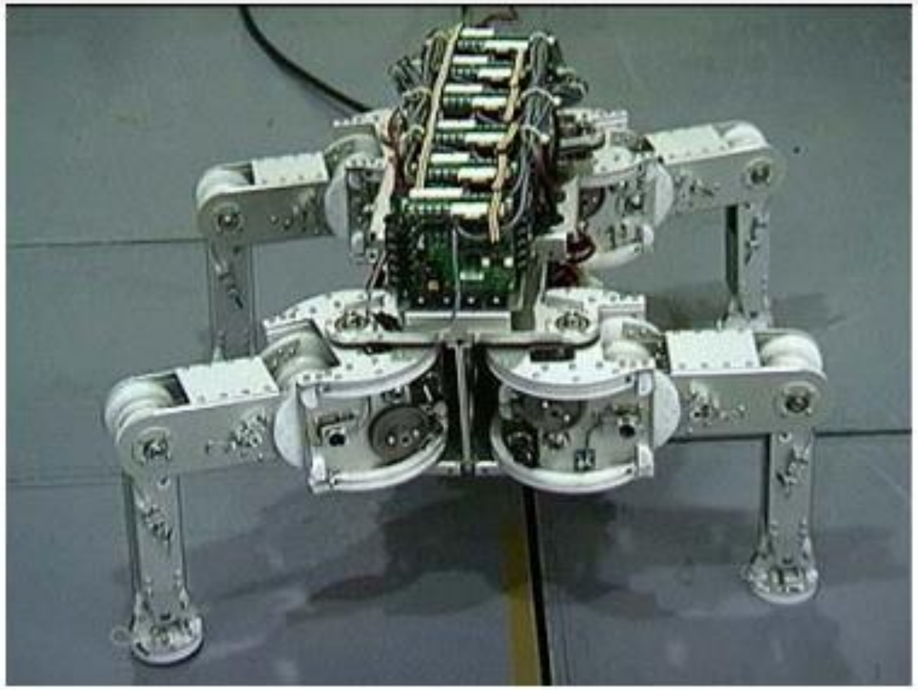
Six legs (hexapod) robot

- 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 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.



Specification:

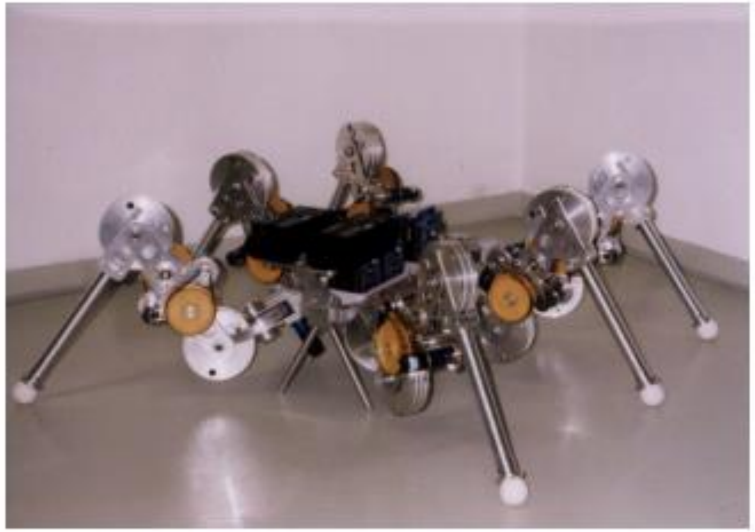
Weight:19 kg
Height:0.25 m
*DOF:4*3*

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

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)*