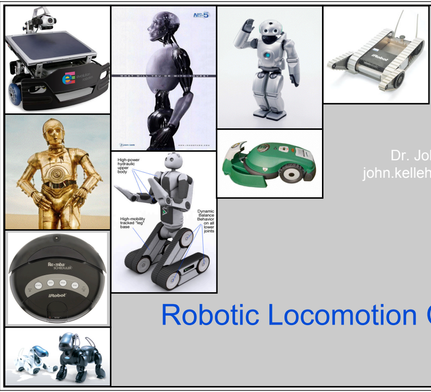

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Robotic Locomotion Concepts

Contents

Today we want to look at some of the principles of locomotion involved in creating mobile robots

- Locomotion concepts
- Degrees of freedom
- Legged robots
- Wheeled robots
- What is the best option?

The Concept Of Locomotion

Robots often need a location mechanism that enable it to move unbounded throughout its environment.

Locomotion: Physical interaction between the vehicle and its environment

Locomotion is concerned with **interaction forces**, and the **mechanisms** and **actuators** that generate them

Locomotion Concepts: Principles Found in Nature

Biological system succeed in moving through a wide variety of harsh environments.

Therefore it can be desirable to copy their selection of locomotion mechanisms.

Locomotion Concepts: Principles Found in Nature

Type of motion	Resistance to motion	Basic kinematics of motion
Flow in a Channel	Hydrodynamic forces	Eddies
Crawl	Friction forces	Longitudinal vibration
Sliding	Friction forces	Transverse vibration
Running	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum
Jumping	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum
Walking	Gravitational forces	Rolling of a polygon (see figure 2.2)

Locomotion Concepts

Some of the locomotion mechanisms found in nature are difficult to imitate technically

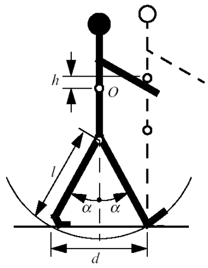
- Mechanical complexity in a biological system is easily achieved through structural replication (cell division). In man made structures each component must by fabricated individually.
- The cell is a microscopic building block which enables extreme miniaturization.
- The biological energy storage system and the muscular and hydraulic activation systems used by large animal and insects achieve torque, response times, and conversion efficiencies that far exceed similarly scaled man-made systems.

Locomotion Concepts

As a result most technical systems use wheels or caterpillars although some use a small number of articulated legs.

However, the movement of a walking biped is close to rolling

Walking Of A Biped



Biped walking mechanism

- Not too far from real rolling
- Rolling of a polygon with side length equal to the length of the step d
- The smaller the step gets, the more the polygon tends to a circle (wheel)

However, fully rotating joint was not developed in nature.

Walking Or Rolling?

Which is better walking or rolling?

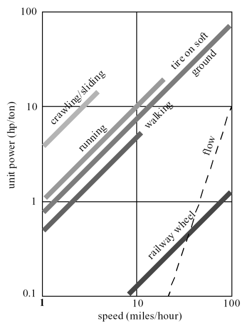
In general, legged locomotion requires higher degrees of freedom and therefore greater mechanical complexity than wheeled locomotion.

Wheels in addition to being simple, are extremely well suited to flat ground.

Walking Or Rolling?

On flat hard surfaces wheeled locomotion is one or two orders or magnitude more efficient than legged locomotion.

As the surface becomes soft, wheeled locomotion accumulates inefficiencies due to rolling friction whereas legged locomotion suffers much less because it consists only of point contacts with the ground.

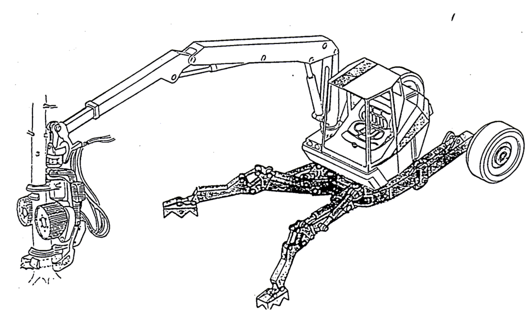


Walking Or Rolling?

The efficiency of wheeled locomotion depends greatly on environmental qualities, particularly the flatness and hardness of the ground.

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.

RoboTrac: A Hybrid Wheel-Leg Vehicle



The Concept Of Locomotion (cont…)

The most important issues in locomotion are:

- Stability
  - Number of contact points
  - Centre of gravity
  - Static/dynamic stabilization
  - Inclination of terrain
- Characteristics of contact
  - Contact point or contact area
  - Angle of contact
  - Friction
- Type of environment
  - Structure
  - Medium (water, air, soft or hard ground)

Mobile Robots With Legs (Walking Machines)

Legged locomotion is characterised by a series of point contacts between the robot and the ground

Advantages of legged locomotion:

- Adaptability & manoeuvrability over rough terrain
- Quality of ground between point contacts does not matter
- Capable of crossing chasms
- Potential to manipulate objects

Disadvantages of legged locomotion:

- Power and mechanical complexity requirements

Mobile Robots With Legs (Walking Machines)

The fewer legs the more complicated becomes locomotion

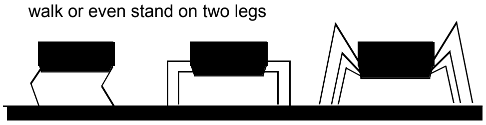
- Stability - at least three legs are required for static stability

During walking some legs are lifted

- Thus loosing stability?

For static walking at least 6 legs are required

- Babies have to learn for quite a while until they are able to walk or even stand on two legs



Mammals (2/4 Legs) | Reptiles (4 Legs) | Insects (6 Legs)

Degrees Of Freedom

The number of **degrees of freedom** (DOF) of a leg is determined by the number of joints it has

A minimum of two DOF is required to move a leg forward

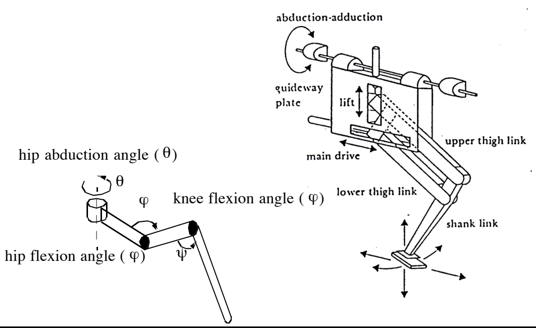
- A lift and a swing motion

Three DOF for each leg in most cases

Fourth DOF for the ankle joint

- Might improve walking
- However, additional joint (DOF) increases the complexity of the design and especially of the locomotion control

Examples Of Legs With 3 DOF



Degrees of Freedom: Trade-off

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 disadvantage of additional joints and actuators are, energy, control and mass. Additional actuators require energey and control, and they also add to leg mass, further increasing power and load requirements on existing actuators.

The Number Of Possible Gaits

The gait is characterized as the sequence of lift and release events of the individual legs

– It depends on the number of legs

– The number of possible events N for a walking machine with k legs is:

$$N = (2k-1)!$$

The Number Of Possible Gaits (cont…)

For a biped walker (k=2) the number of possible events N is:

$$N = (2k-1)! = 3! = 3 \cdot 2 \cdot 1 = 6$$

The 6 different events sequences are:

– both legs down - right down / left up - both legs down
– both legs down - right up / left down - both legs down
– both legs down - both legs up - both legs down
– right down / left up - right up / left down - right down / left up
– right down / left up - both up - right down / left up
– right up / left down - both up - right up / left down

The Number Of Possible Gaits (cont…)

The number of possible gates grows quite large.

For a robot with 6 legs (hexapod) N is already

$$N = 11! = 39{,}916{,}800$$

One Legged Robot

The minimum number of legs a legged robot can have is one.

Minimizing the number of legs is beneficial for several reasons:

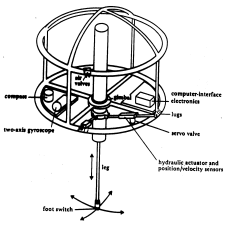
– Body mass is particularly important to walking machines, and the single leg minimizes cumulative leg mass.
– Leg coordination is required when a robot has several legs, but with one leg no such coordination is needed.
– A single-legged robot requires only a sequence of single contacts, making it amenable to roughest terrain - a hoping robot can dynamically cross a gap that is larger than its stride by taking a running start.

The major challenge in creating a single-legged 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 corrective forces.

Example One Legged Robot

The MIT Hopper (1995)



The robot makes continuous corrections to body attitude and to robot velocity by adjusting the leg angle with respect to the body.

Visit the MIT Leg Laborotory at: http://www.ai.mit.edu/projects/leglab/robots/robots.html

Bipedal Robots

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.

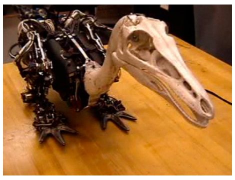
Both companies designed small, powered joints that achieve power-to-weight performance unheard of commercially available servomotors.

These new “intelligent” servos provide not only strong actuation but also compliant actuation by means of torque sensing and closed-loop control

25 of 68

Example Bipedal Robots

MIT Leg Laboratory's "Troody" Dinosaur like robot



Visit the MIT Leg Laborotory at: http://www.ai.mit.edu/projects/leglab/robots/robots.html

26 of 68

Bipedal Robots

An important feature of bipedal robots is their anthropomorphic shape.

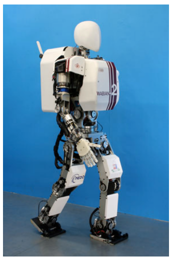
They can be built to have the same approximate dimensions as humans, and this makes them excellent vehicles for human-robot interaction.

The WABIAN robot was built for research in this area.

27 of 68

Humanoid Robots

Wabian 2R built at Waseda University in Japan

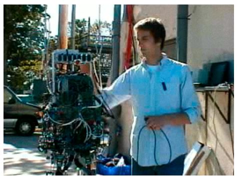


More on Wabian 2R: www.takanishi.mech.waseda.ac.jp/research/wabian/index.htm

28 of 68

Humanoid Robots (cont…)

MIT Leg Laboratory's "M2" humanoid robot

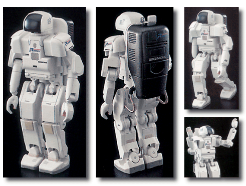


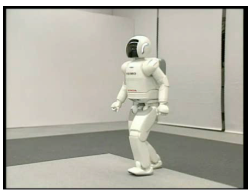
Visit the MIT Leg Laborotory at: http://www.ai.mit.edu/projects/leglab/robots/robots.html

29 of 68

Humanoid Robots (cont…)

P3 (late 1990s) and ASIMO (present) from Honda, Japan





Lots of movies about the evolution of ASIMO: http://asimo.honda.com/AsimoHistory.aspx

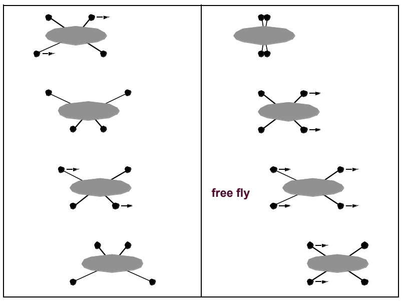
30 of 68

Bipedal Robots

Bipedal robots can only be statically stable within some limits, and so bipedal robots 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.

Most Obvious Gaits With 4 legs

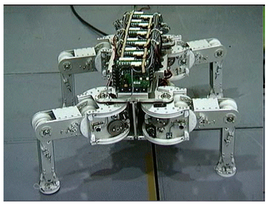


Changeover Walking   Galloping

Walking Robots With Four Legs (Quadruped)

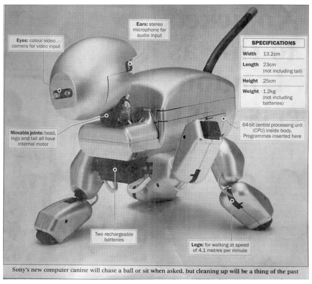
Titan VIII, a quadruped robot, Tokyo Institute of Technology

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

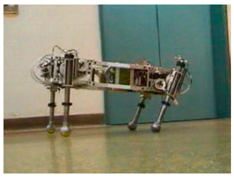


Walking Robots With Four Legs (Quadruped) (cont…)

Artificial Dog Aibo from Sony, Japan

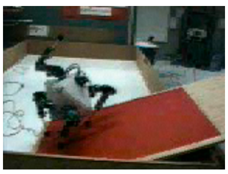


Walking Robots With Four Legs (Quadruped) (cont…)



Walking Robots With Four Legs (Quadruped) (cont…)

Sometimes really interesting (and unexpected) things can be done with four legs

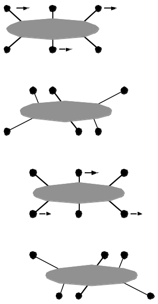


Six Legged (hexapod) Robot

Six-legged configurations have been popular in robotics because of their static stability during walking, thus reducing the control complexity.

In most cases, each leg has three degrees of freedom, including hip flexion, knee flexion and hip abduction.

37 of 68 Most Obvious Gait With 6 Legs (Static)



38 of 68 Walking Robots With Six Legs (Hexapod)

Most popular as static stable walking is possible

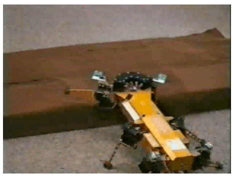
Legs can be particularly simple

The human guided hexapod of Ohio State University

39 of 68 Walking Robots With Six Legs (Hexapod)

Genghis is a commercially available robot that has six legs, each of which has two degrees of freedom.

Such a robot which consists of only hip flexion and hip abduction has less maneuverability on rough ground but performs well on flat ground.



40 of 68 Walking Robots With Six Legs (Hexapod)

Lauron III by the University of Karlsruhe

More information on Lauron III available at:
http://www-iri.upc.es/groups/arobots/legged_robots/default.htm

41 of 68 Legged Robots

It is clear from the examples that legged robots have much progress to make before they are competitive with their biological equivalents.

Nevertheless, significant gaines have been realised, primarily due to advances in motor design.

42 of 68 Mobile Robots With Wheels

Wheels are the most appropriate solution for most robotic applications

There are lots of options for combinations of different kinds of wheels in different orientations

Selection of wheels depends on the application

Key Considerations

A mobile robot designer must consider the wheel type and the wheel arrangments in parallel when designing a wheeled locomotion mechanism.

The decisions made regarding wheel type and configuration govern the three primary characteristics of wheeled locomotion:

- Stability
- Maneuverability
- Controllability

Characteristics Of Wheeled Robots & Vehicles

Stability of a vehicle is guaranteed with 3 wheels
- Center of gravity is within the triangle formed by the ground contact point of the wheels

Stability is improved by 4 and more wheels
- However, these arrangements are hyperstatic and require a flexible suspension system

Bigger wheels allow overcoming higher obstacles
- But they require higher torque or reductions in the gear box

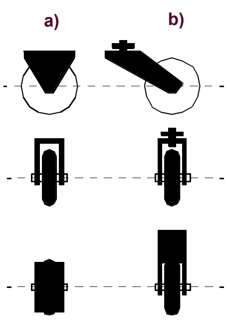
Most arrangements are non-holonomic
- Require high control effort

Combining actuation and steering on one wheel makes the design complex and adds additional errors for odometry

The Four Basic Wheels Types

a) Standard wheel: Two degrees of freedom; rotation around the (motorized) wheel axle and the contact point

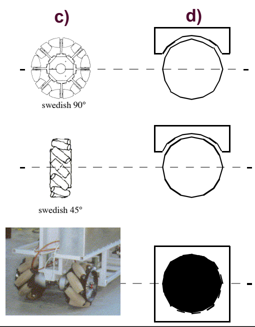
b) Castor wheel: Three degrees of freedom; rotation around the wheel axle, the contact point and the castor axle



The Four Basic Wheels Types

c) Swedish wheel: Three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers and around the contact point

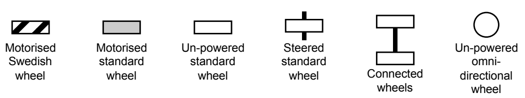
d) Ball or spherical wheel: Suspension technically not solved



Different Wheel Arrangements

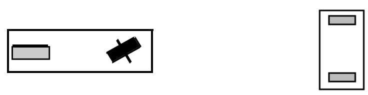
In the next few slides we will look at some of the wheel configurations used by robots and how they affect stability, maneuverability and controllability.

The diagrams will use the following representations for the different wheel types



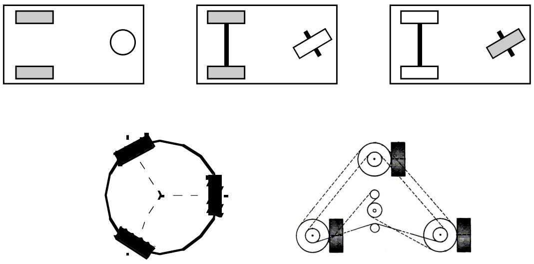
Different Wheel Arrangements

Two wheels



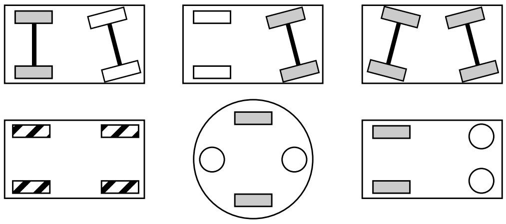
Different Wheel Arrangements (cont…)

Three wheels



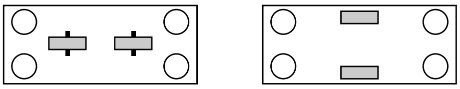
Different Wheel Arrangements (cont…)

Four wheels



Different Wheel Arrangements (cont…)

Six wheels

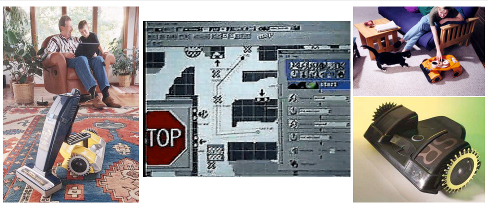


Stability

Surprisingly, the minimum number of wheels required for static stability is two.

A two-wheel differential drive robot can achieve static stability if the center of mass is below the wheel axis.

Cye: A 2 Wheel Differential Drive Robot



Cye, a commercially available domestic robot that can vacuum and make deliveries in the home, is built by Probotics, Inc and has just two wheels

More information on Cye available at: http://www.personalrobots.com

Stability

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.

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.

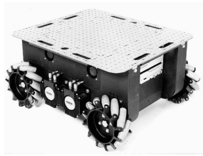
This level of maneuverability requires wheels that can move in more than one direction, and so omnidirectional robots usually employ Swedish or spherical wheels that are powered.

Uranus

Omni-directional drive with 4 wheels

Movement in the plane has 3 DOF

- Thus only three wheels can be independently controlled
- It might be better to arrange three Swedish wheels in a triangle



Maneuverability

In general, the ground clearance of robots with Swedish and spherical wheels is limited due to the mechanical constraints of constructing omnidirectional wheels.

Controllability

There is generally an inverse correlation between controllability and maneurverability.

Controlling an omnidirectional robot for a specific direction of travel is more difficult then less maneuverabile design.

For example, an Ackerman steering vehicle can go straight simply by locking the steerable wheels and driving the drive wheels.

Summary

We have looked at the MANY options for giving robots the powers of locomotion

With legged robots the key consideration is stability

For wheeled robots we must consider:

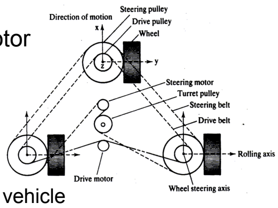
- Stability
- Maneuverability
- Controllability

The situations in which we expect our robots to operate are the key driver in deciding the type of locomotion we choose

Questions?

?

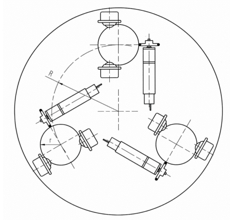
Synchro Drive

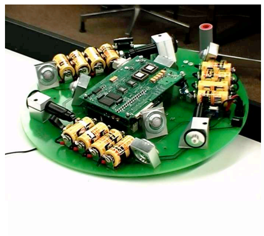


- All wheels are actuated synchronously by one motor
  - Defines the speed of the vehicle
- All wheels steered synchronously by a second motor
  - Sets the heading of the vehicle
- The orientation in space of the robot frame will always remain the same
  - It is therefore not possible to control the orientation of the robot frame

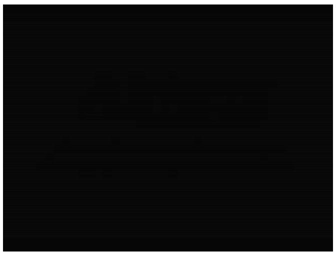
Tribolo

- Omni-directional Drive with 3 spheric wheels





Airtrax Sidewinder Forklift

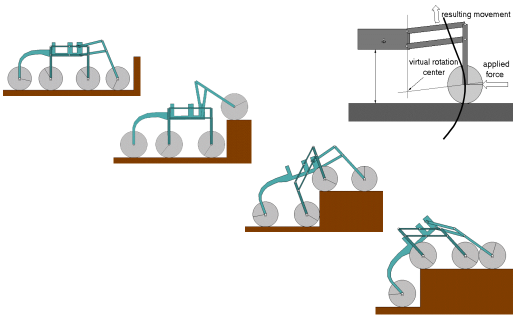


Information on Swedish wheels available at: http://www.omniwheel.com
Information on Airtrax omnidirectional forklifts available at: http://www.airtrax.com
IdMind's 3 wheeled holonomic robot: http://www.idmind.pt/english/research/hr.php

SHRIMP

- SHRIMP is a mobile robot with excellent climbing abilities
  - 6 wheels
    - 1 fixed wheel in the rear
    - 2 boogies on each side
    - 1 front wheel with spring suspension
  - Robot sizing around 60 cm in length and 20 cm in height
  - Highly stable in rough terrain
  - Overcomes obstacles up to 2 times its wheel diameter

SHRIMP (cont…)



SHRIMP (cont…)

More information on SHRIMP available at: http://www.bluebotics.com/solutions/Shrimp

Interesting Directions With Wheels

The SHRIMP is just one example of the current trend for wheeled robots is to go for multiple wheels with elaborate suspension

Caterpillar Tracks

Caterpillar tracks are another an attractive solution for mobile robots

– Why?

Click image to play video

Visit iRobot at: http://www.irobot.com