

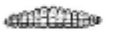
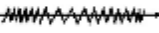










Mobile robots

Mobile robot (MOBOT) – robotic device, which has the base able to move in 2 or more degrees of freedom (manipulator with the travel is not recognized like the mobile robot)



Locomotion of living organisms

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) 

Motion on the ground (UGV – Unmanned Ground Vehicle or TOV - TeleOperated Vehicle)



- **wheeled** chassis: Segway, tricycle, car-like structure (static stability requires 3 or more wheels, for 4 and more wheels it's necessary to apply the suspension system). While the centre of gravity is under the axis connecting the two wheels, such system has ensured static stability, too !!!
- **tracked**: 2 tracks, 2 main tracks with auxiliary tracks, multistage constructions
- **walking** (legged): 2 legs, 4 legs, 6 legs, more legs (statically stable motion is requiring 4+ legs)
- **hybrid constructions** (wheels+tracks, wheels+legs, roller blades...)
- **sliding motion** (snake or caterpillar)
- **other types of motion** (gyroscopic rolling, jumping, "soft robot", wall climbing)
- **hovercraft** (amphibian)

Motion on the water surface and under the surface

- robotic boats (USV – Unmanned Surface Vessel) – driven by motor or sail
- robotic submarines (UUV – Unmanned Undersea Vehicle)
- robotic fish or water snake – eel
- robotic crab for the work on the sea bed
- robotic amoeba or medusa



Motion in the air (UAV – Unmanned Aerial Vehicle)

- lighter than air: helium/hot-air balloon, airship
- heavier than air: (a) airplane (glider, propeller, jet)
- (b) helicopter (1 rotor, 2 rotors, 4 rotors)
- (c) ornithoptera (robotic byrd)
- (d) entomptera (robotic dragonfly)
- (e) controlled parachute



Motion in cosmic space

- reactive drive (pressed gas, chemical fuel, ionic engine, atomic engine) or solar sailship

Combined motion in various surroundings (robot - amphibian) hovercraft, hydroplanes and combinations of the boat and the ground vehicle



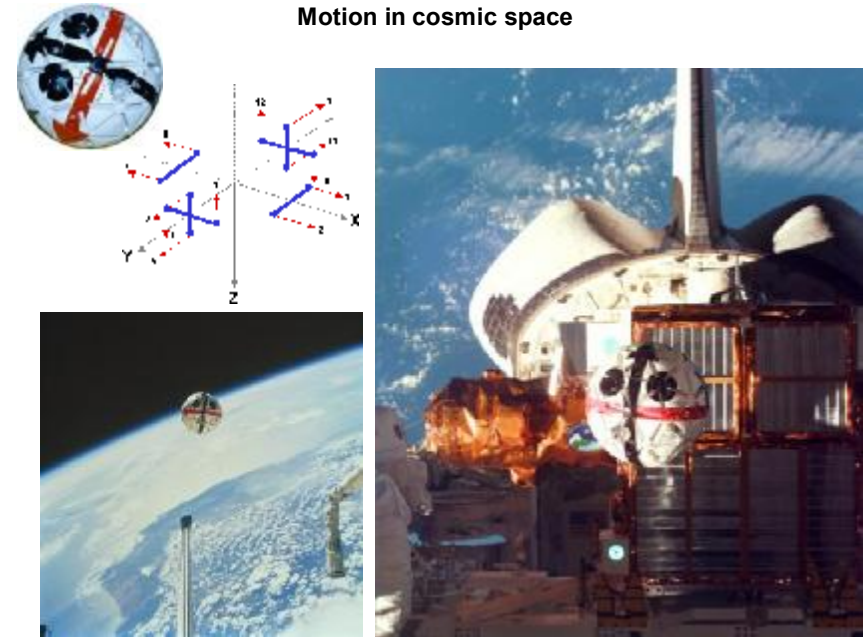
Motion on the water surface and under it



Motion in the atmosphere



Motion in cosmic space



AERCam Sprint – control by means of 12 jets through which compressed gas is flowing

Wheeled mobile robots

Types of wheels: a) standard wheel – passive, driving, steering or both
 b) castor/caster wheel (swivel wheel) – mostly passive (supporting)
 c) spherical wheel (ball castor/caster)
 d) omni-directional wheel

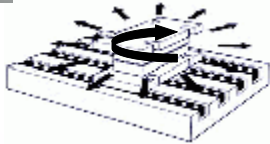




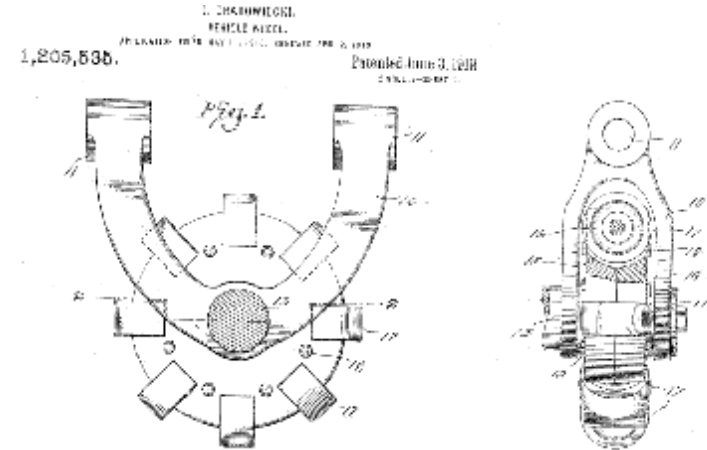
Swivel wheel applications



Omni-directional and spherical wheel applications



First patent of the omni-directional wheel



Another patent of the omni-directional wheel

In the book of Ezekiel it's written: I also saw four wheels beside them, one wheel beside each cherub; the wheels appeared to have the luster of chrysolite stone. All four of them seemed to be made the same, as though they were a wheel within a wheel. When they moved, they went in any one of their four directions without veering as they moved; for in whichever direction they were faced, they went straight toward it without veering as they moved. (Ez.1, 15-17)



Josef F. Blumrich



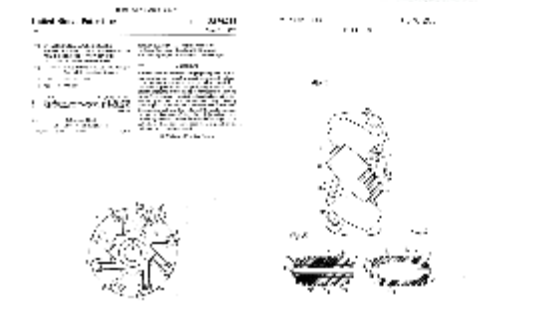
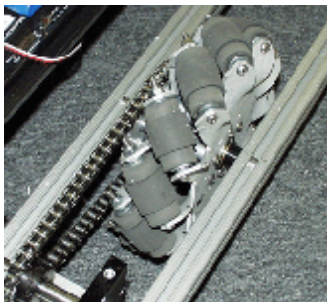
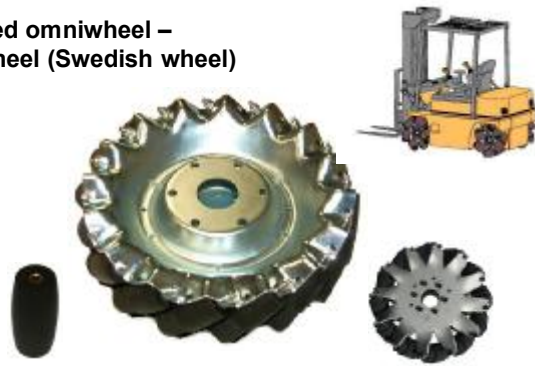
Patent No. 3 789 947



Omni-directional wheel – construction variants



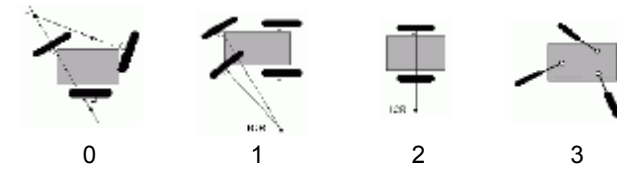
Modified omniwheel – Mecanum wheel (Swedish wheel)



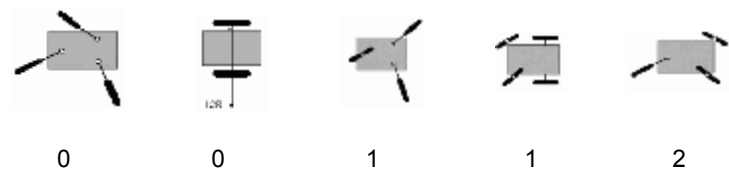
patent No.3 876 255 Swedish inventor Bengt Ilon

Maneuverability of mobile robots

Degree of mobility – number of degrees of freedom in planar space

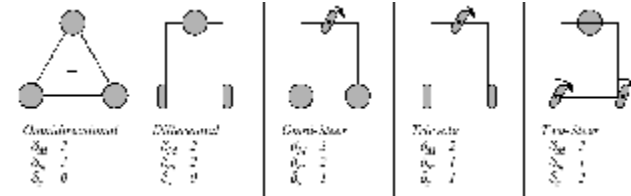


Degree of steerability – number of independent steering wheels.



©/P. Slegner, / Kowalski

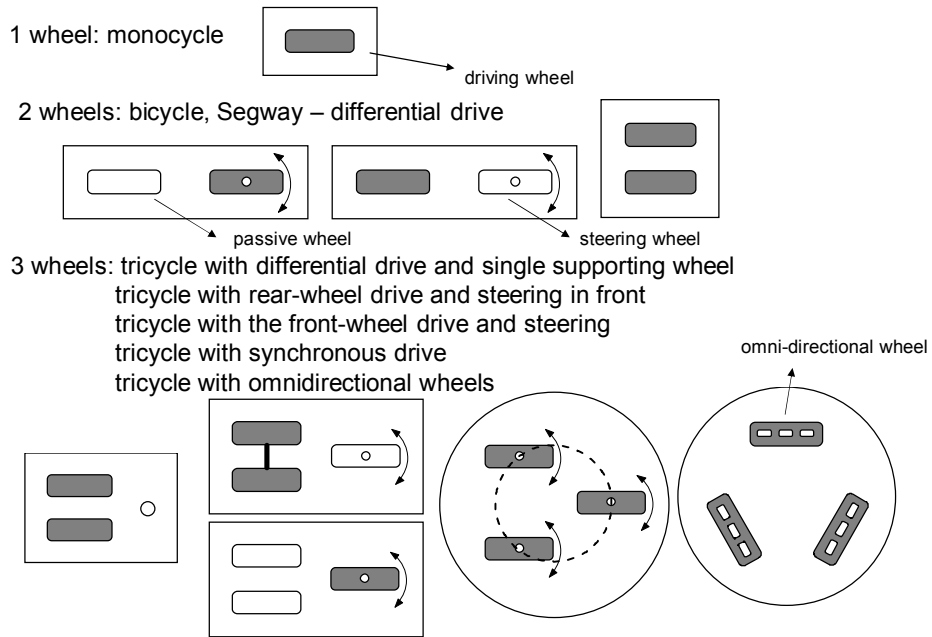
Degree of maneuverability = degree of mobility + degree of steerability



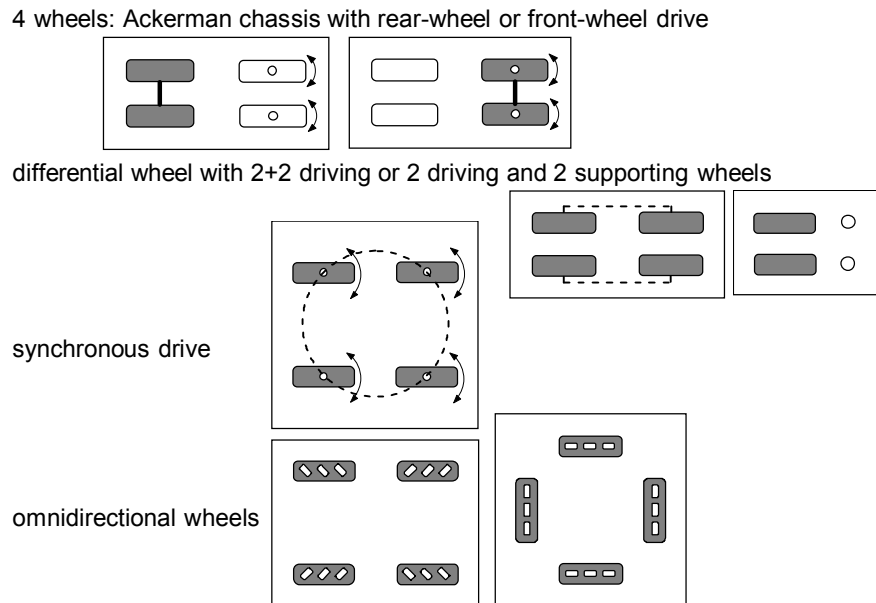
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Holonomic chassis is enabling independent control of all 3 degrees of freedom

Commonly used structures of wheeled chassis

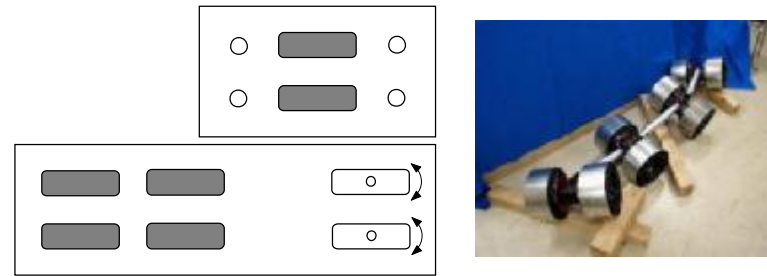


Commonly used structures of wheeled chassis

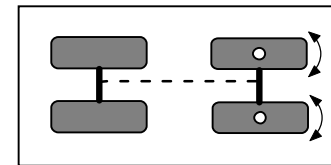


Commonly used structures of wheeled chassis

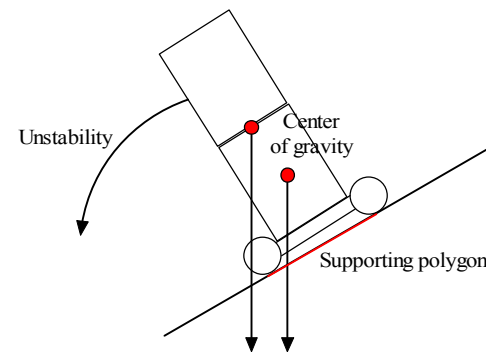
Increasing of total number of wheels – improving the carrying capacity and terrain crossing ability



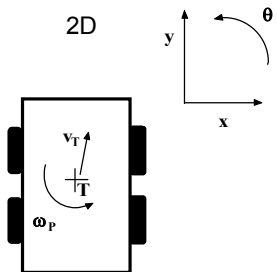
Increasing of number of driving wheels: Ackerman chassis with 4 driven wheels (4WD/AWD system) – increasing of the traction in the slick terrain (sand, mud, snow...)



Stability of the robot with wheeled chassis



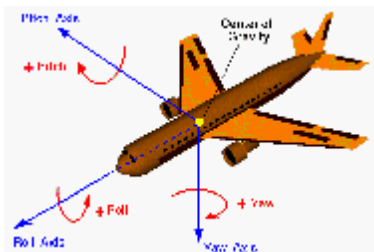
Mathematical model of the mobile robot



$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v_T \\ \omega_P \end{pmatrix}$$

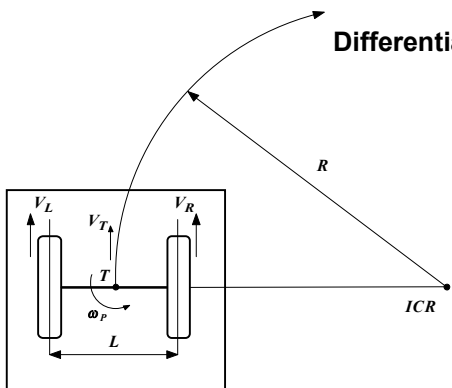
v_T - tangential velocity of the center of gravity

ω_P - angular velocity of the robot rotation around center of gravity



3D

Differential drive



$$R = \frac{L}{2} \cdot \frac{v_R + v_L}{v_R - v_L}$$

$$v_T = \frac{v_R + v_L}{2}$$

$$\omega_P = \frac{v_R - v_L}{L}$$

ICR – Instantaneous center of rotation

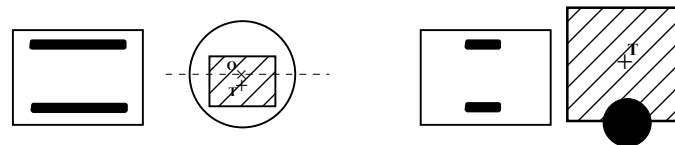
R – radius from ICR

If $v_R = v_L$, then $R = \infty$ (straight-line motion)

If $v_R = -v_L$, then $R = 0$ (rotation around center)



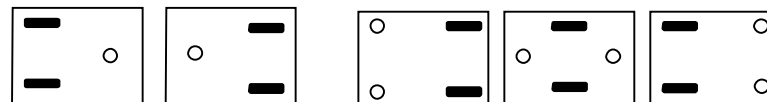
Variants of differential drive



Structures without any supporting wheels

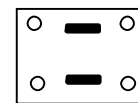
- center of gravity below the axis of the wheels (stable structure)

- center of gravity above the axis of the wheels (unstable structure – Segway)

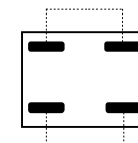


1 supporting wheel
(swivel, spherical, omni-directional)

2 supporting wheels



4 supporting wheels



Coupled pairs of driving wheels



Tracked chassis

Differential drive



Differential drive



Differential drive



Differential drive



Seqway chassis



Dean Kamen



Bombardier Embrio

Segway Human Transporter



Concept Centaur



Independence iBOT

Linearized model of the Segway chassis

$$\begin{pmatrix} \dot{x} \\ \dot{\phi} \\ \dot{\psi} \\ \dot{v}_L \\ \dot{v}_R \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{23L} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & A_{43L} & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ \phi \\ \psi \\ v_L \\ v_R \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ B_{21L} & B_{22L} \\ 0 & 0 \\ B_{14L} & B_{42L} \\ 0 & 0 \\ B_{61L} & B_{62L} \end{pmatrix} \begin{pmatrix} M_L \\ M_R \end{pmatrix}$$

- x - position in the straight direction
- ϕ - pitch angle
- ψ - yaw angle
- M_L - moment (torque) acting on the left wheel
- M_R - moment acting on the right wheel

Segway as a human transporter



Personal transporter Winglet by Toyota



Application of Segway platform in robotics



PEA Bot by WowWee



nBot by Davida P. Anderson



Emiew by fy Hitachi



NASA Robonaut

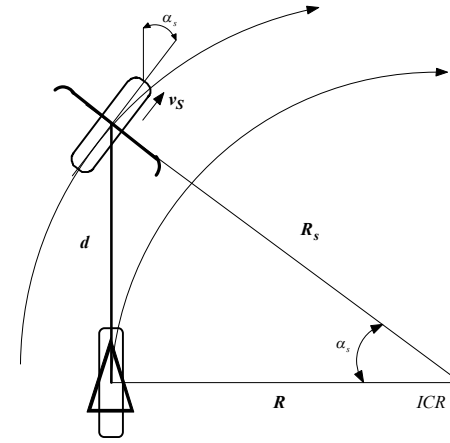


Robot-football player from Carnegie Mellon

Chassis with 6 wheels



Bicycle kinematics



$$R_s = d / \sin(\alpha_s)$$

$$R = d / \tan(\alpha_s) = d \cdot \cot(\alpha_s)$$

$$v_T = v_s \cos(\alpha_s)$$

$$\omega_p = \frac{v_s}{d} \sin(\alpha_s)$$

d – wheel base
v_s - velocity of steering wheel



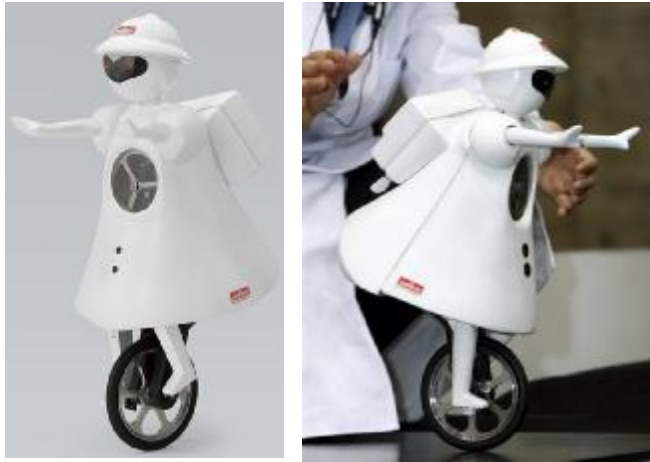
Tracked chassis



Robot – cyclist by Murata company

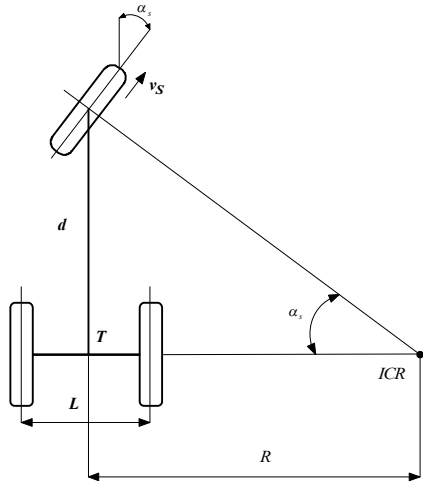


Monocycle construction



Murata girl

Tricycle with the front drive



$$R = d \cdot \cot(\alpha_s)$$

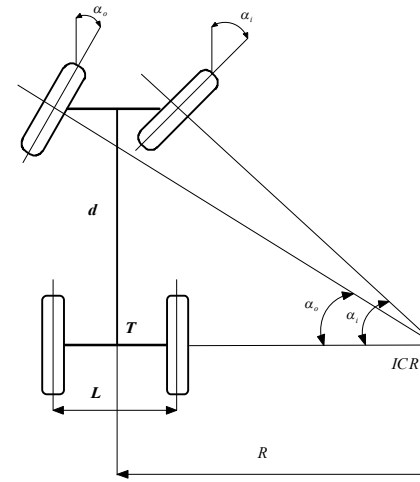
$$v_T = v_s \cos(\alpha_s)$$

$$\omega_P = \frac{v_s}{d} \sin(\alpha_s)$$



d – wheel base
L – wheel tread (track)
v_s – velocity of steering wheel

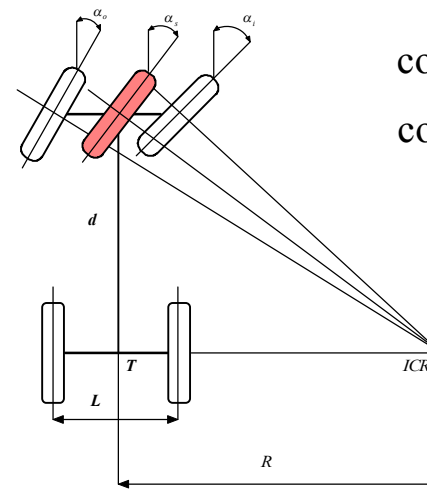
Car drive (Ackerman steering)



$$\cot(\alpha_o) - \cot(\alpha_i) = L/d$$



Reduction of Ackerman steering to tricycle

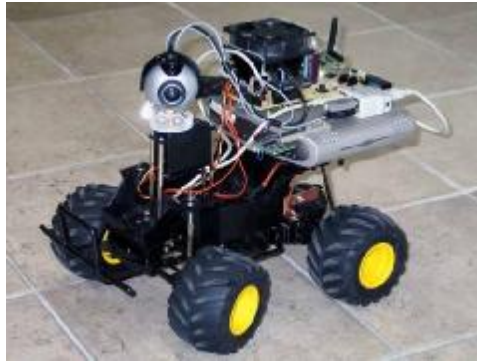


$$\cot(\alpha_s) = \cot(\alpha_i) + L/2d$$

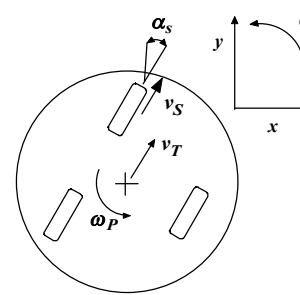
$$\cot(\alpha_s) = \cot(\alpha_o) - L/2d$$



Ackerman steering – construction example



Synchronous drive



$$v_x = v_s \cdot \cos(\alpha_s)$$

$$v_y = v_s \cdot \sin(\alpha_s)$$

$$v_T = v_s$$

$$\omega_P = 0$$

v_s – velocity of the wheels

Radius of the path curvature $R = \infty$



Ackerman steering with system 4WS

4 wheel steering



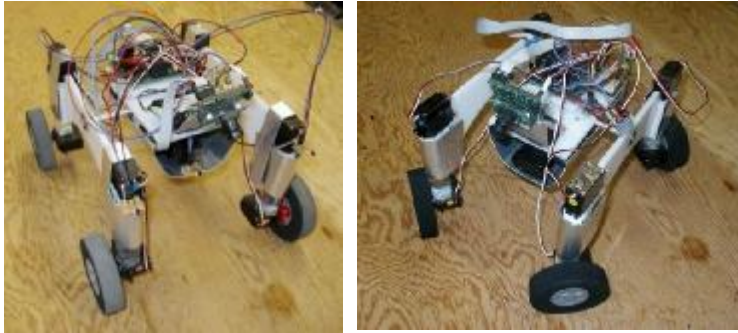
System 4WS used in Mazda 626 GT (1989)

System Active drive in Renault Laguna III GT (2008)

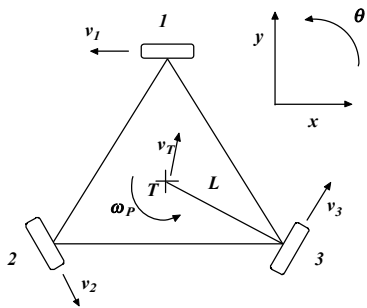
Example of the synchronous drive



Chassis with 4 independent steering wheels



Chassis with 3 omni-directional wheels



$$v_x = -\frac{2}{3}v_1 + \frac{1}{3}v_2 + \frac{1}{3}v_3$$

$$v_y = -\frac{1}{\sqrt{3}}v_2 + \frac{1}{\sqrt{3}}v_3$$

$$v_T = \sqrt{(v_x^2 + v_y^2)}$$

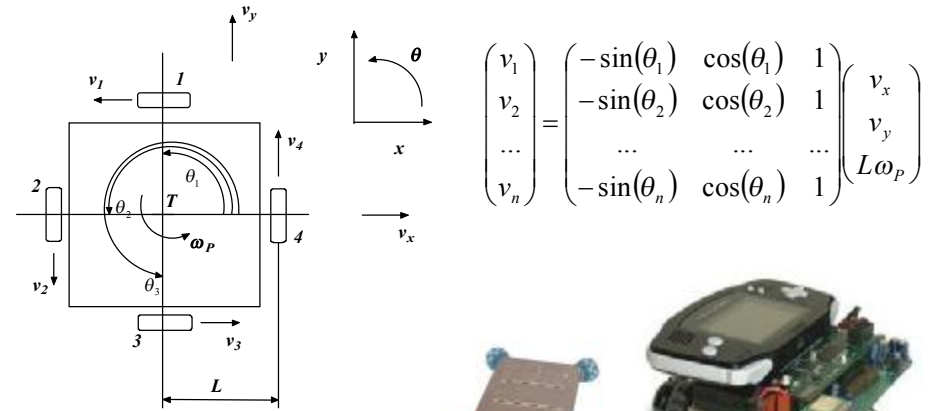
$$\omega_p = \frac{1}{3L}(v_1 + v_2 + v_3)$$

v_i - velocity of i-th wheel
 L - distance of wheel from center of base

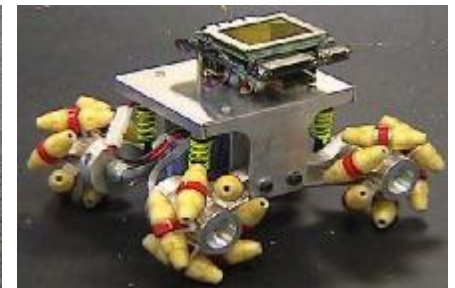
Radius of curvature $R = \infty$



Chassis with 4+ omni-directional wheels

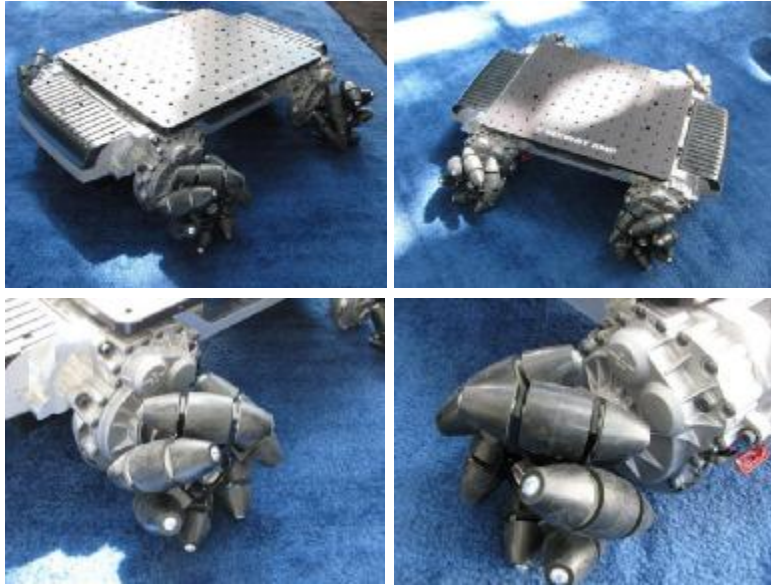


Chassis with 4 omni-directional (Mecanum) wheels

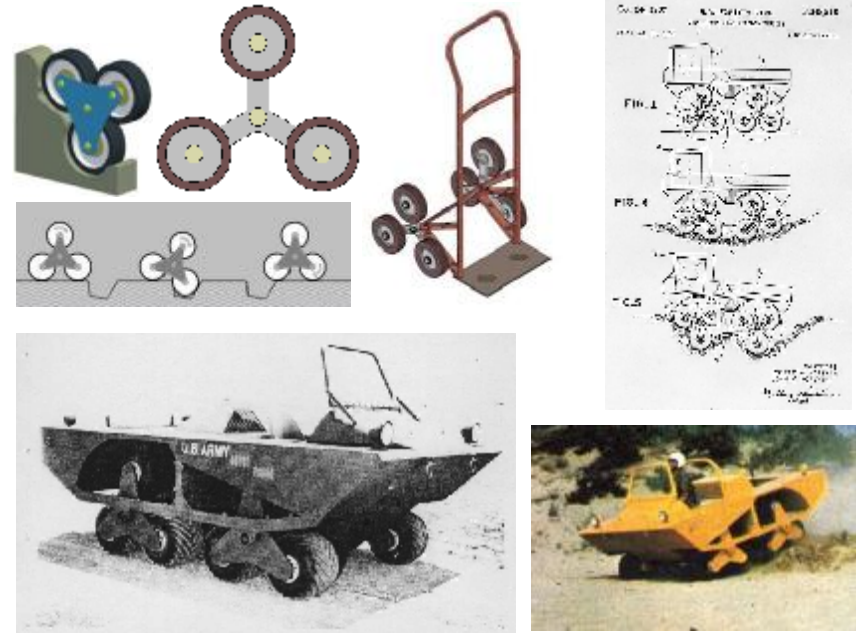




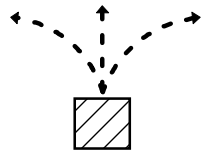
Example of the chassis with 4 omni-wheels (Mecanum)



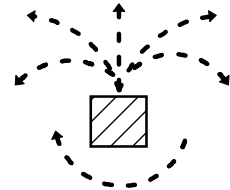
Application of the Weinstein's wheel (tri-star wheel)



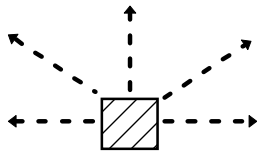
Summary of the chassis characteristics



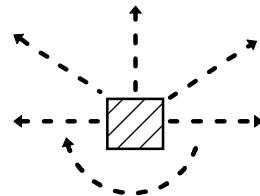
Tricycle, car chassis: motion along arcs with the radius of curvature $R_{min} \neq \infty$. It's not possible to turn around the center and to move in side direction.



Differential chassis: motion along with arcs with radius $0 \neq \infty$. It's possible to turn around the center, but not to move in side direction.



Synchronous chassis: motion along with straight lines in all directions. It's possible to move in side direction, but it's not available rotation around it's center.



Omni-directional (holonomic) chassis: motion along with the straight lines in all directions (together with the side direction) + rotation around it's center.

Active wheel by Mitsubishi



Active wheel by Michelin



Application in vehicle
Venturi Volage



Motion based on the cyclical deformation of the wheel's shape

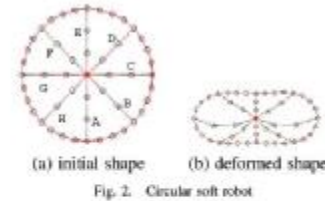
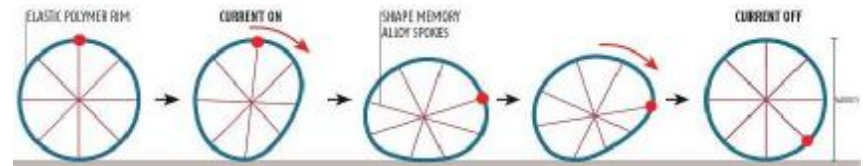


Fig. 2. Circular soft robot

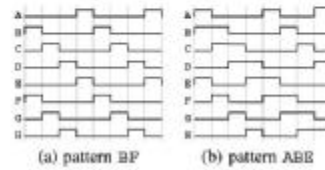
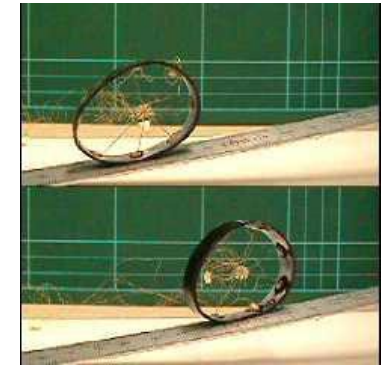


Fig. 3. Voltage patterns applied to SMA coils

©Yuuta Sugiyama et al.



Gyroscopic drive



Legged (walking) robots

Static stability – at least 3 legs has to be in contact with the ground and the center of gravity should be within the polygon created by the contact points of the legs with the ground.



Dynamic stability – either the body or the legs have to be in the motion to keep the center of gravity within supporting polygon.



Legged robots

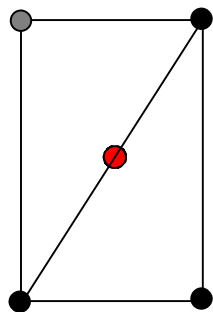
Advantage of the legged robots in comparison with wheeled ones:

- it's possible to overcome smaller obstacles (convenient for the outdoor application – it's not required the road).
- constructions with more legs enable smooth motion of the platform also in the rough terrain
- it's possible to move over the stairs and various steps (it's not needed barrier free space in the case of indoor apps)

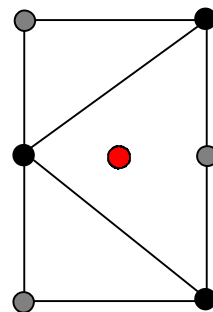
Disadvantage of the legged robots in comparison with wheeled ones:

- more complex mechanics and more engines for comparable number of degrees of freedom
- greater consumption of energy for the comparable operations
- typically they are allowing only slower motion
- more complex algorithms of the motion control

Static stability



4 legs

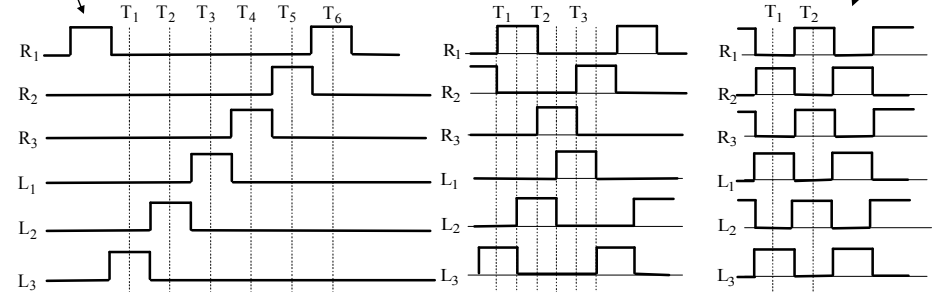


6 legs

The slowest, but the most stable gait

6-leg robot gaits

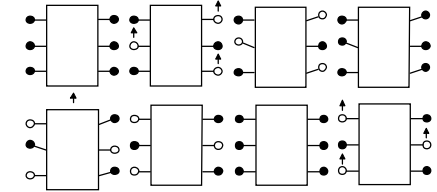
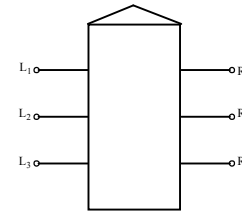
The fastest, but less stable gait



At least 5 legs in contact with the ground (wave gait)

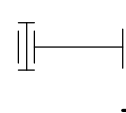
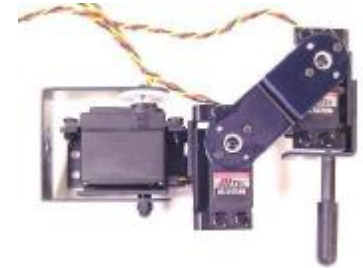
At least 4 legs in the contact (ripple gait)

At least 3 legs in contact (tripod gait)

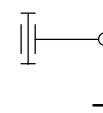


Kinematic leg structure

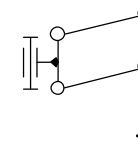
Leg has to have at least 2 DOF (for moving up and forward)



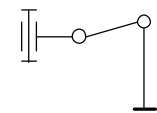
Rot. + Tran.



2 rotations



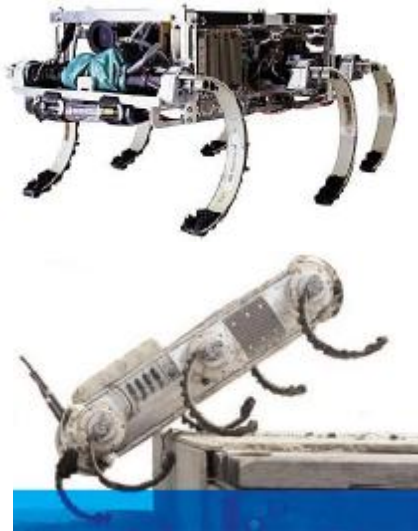
parallelogram (2 DOF)



3 rotations

Kinematic leg structure

United States Patent
 6,481,715 B2
 Patent No. 6,481,715 B2
 Filed: 08/11/00
 Inventor: Robert M. Murray, Jr., et al.
 Assignee: Lockheed Martin Corporation



Robot RHex with 6 flexible legs (with 1 DOF each)

Kinematic leg structure



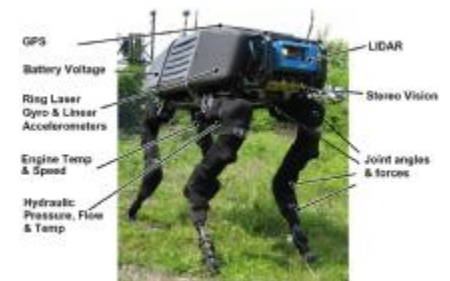
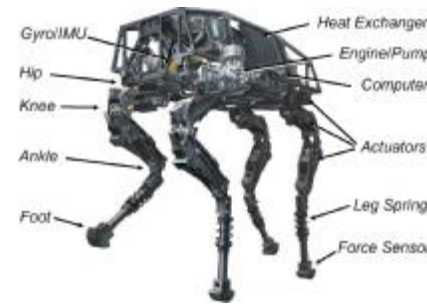
Combination wheel-leg by company Vex Robotics

Walking robots – examples



Biped, Quadruped and Hexapod

Walking robots – examples



Walking military robot Big Dog by Boston Dynamics

Walking robots – examples

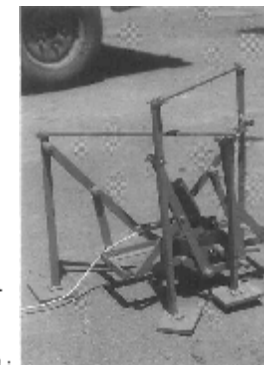
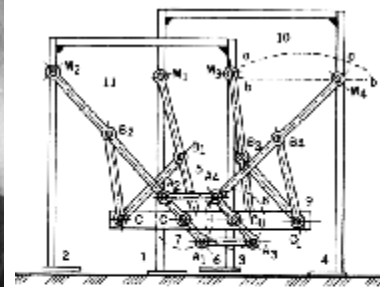


Monopod and Tripod

Application of parallel kinematics



Walking mechanism with single degree of freedom



$$A_1 B_1 = B_1 C_1 = B_1 N_1 = A_1 O_1 = O_1 C_1 = O_1 M_1 = A_1 O_1 B_1 =$$

$$= B_3 C_1 = B_3 M_1 = A_4 B_4 = B_4 C_1 = B_4 M_4 = 1 ;$$

$$A_1 C_1 = A_2 C_1 = A_3 C_1 = A_4 C_1 = 0.355 ;$$

$$O_1 C_1 = O_1 C_1 = 0.755, \quad A_2 A_4 = A_2 A_3 = O_1 C_1 = 0.634 .$$

Chebyshev's walking 4-legged machine from mid of 19th century

Special kind of the motion



Climbing with help of supporting points

Special kind of the motion



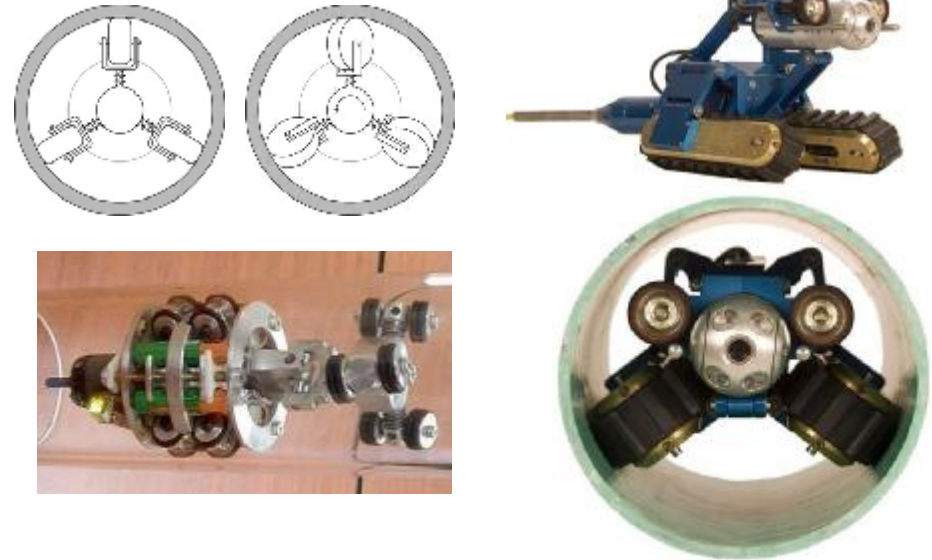
Wall climbing

Special kind of the motion



Vortex VRAM (Vortex Regenerative Air Movement) Mobile Robot Platform – motion over arbitrarily orientated surfaces

Special kind of the motion



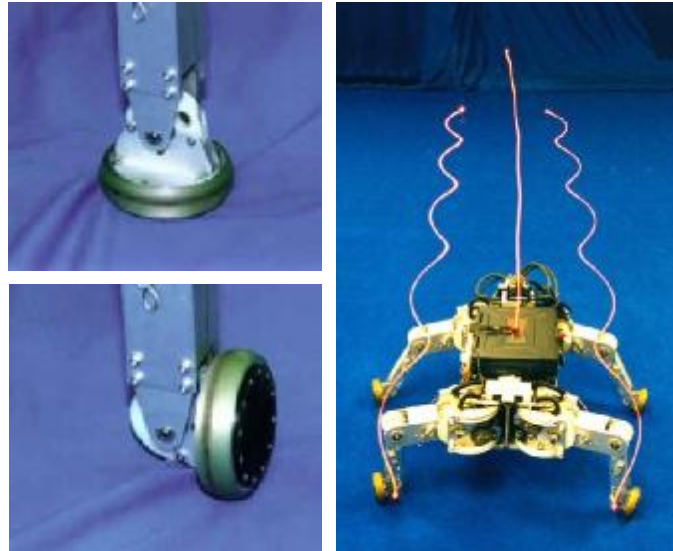
Motion in pipe

Special kind of the motion



Hybrid structures

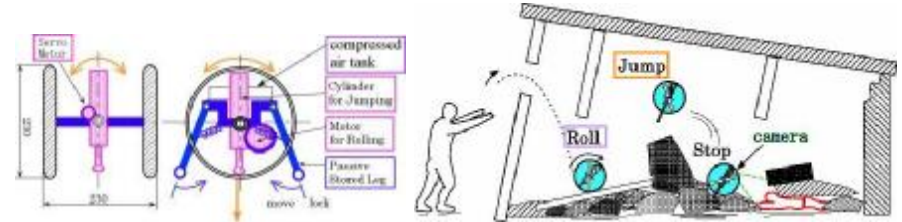
Special kind of the motion



Robot - skater

© Hirose Fukushima Robotics Lab.

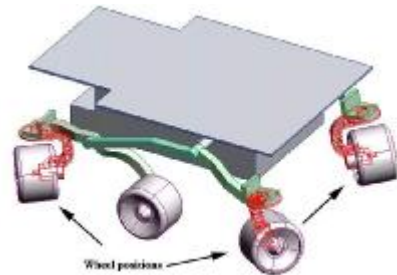
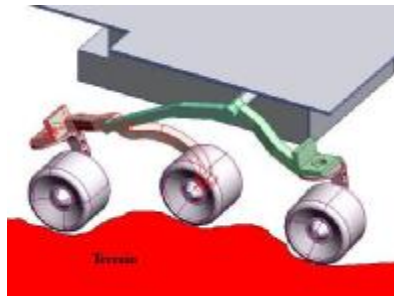
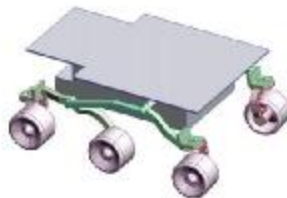
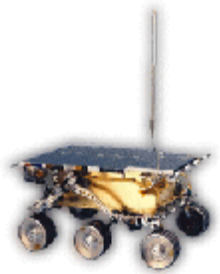
Special kind of the motion



Jumping robot

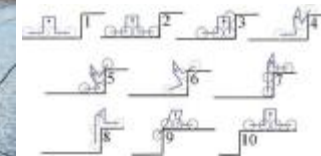
© Kitagawa Tsukagoshi Lab.

Special kind of the motion



Mars rover Sojourner

Special kind of the motion

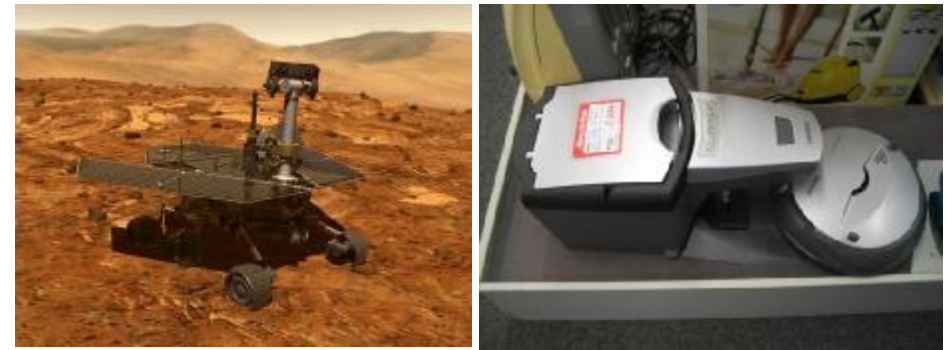


Special kind of the motion

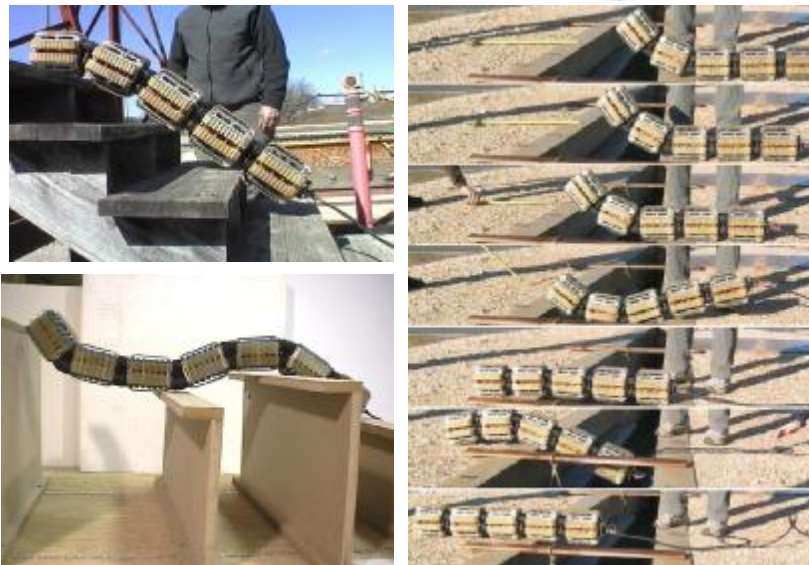


Autonomy of the mobile robots

- **energy autonomy** (ability to ensure it's own energy source)
- **control autonomy** (goal navigation, obstacle avoidance)
- **maintenance autonomy** (self-maintenance and small failure repair)



Special kind of the motion



Robot OmniTread from University of Michigan

General control structure of the mobile robot

