EE-381 Robotics-1
UG ELECTIVE

Lecture 11

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Last Lecture

- Linear and Angular Velocities

$$^{A}V_{Q} = {}^{A}V_{BORG} + {}^{A}_{B}R\,{}^{B}V_{Q} + {}^{A}\Omega_{B} \times {}^{A}_{B}R\,{}^{B}Q$$

- Velocity propagation from link to link
  - Revolute joint

$$^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_{i} + \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}$$

$$^{i+1}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_{i} + {}^{i}\omega_{i} \times {}^{i}P_{i+1}).$$

  - Prismatic joint

$$^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_{i},$$

$$^{i+1}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_{i} + {}^{i}\omega_{i} \times {}^{i}P_{i+1}) + \dot{d}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}.$$

Last Lecture

- Jacobians

$$ {}^{0}v = {}^{0}J(\Theta)\dot{\Theta}, $$

- Jacobians and Singularities
  - Workspace-boundary singularities
  - Workspace-interior singularities
- Static Forces in Manipulators

$$ {}^{i}f_i = {}^{i}_{i+1}R\, {}^{i+1}f_{i+1}, $$
$$ {}^{i}n_i = {}^{i}_{i+1}R\, {}^{i+1}n_{i+1} + {}^{i}P_{i+1} \times {}^{i}f_i. $$

Last Lecture

- Torque
  - Revolute joint $\tau_i = {}^i n_i^T \, {}^i\hat{Z}_i.$
  - Prismatic joint $\tau_i = {}^i f_i^T \, {}^i\hat{Z}_i.$

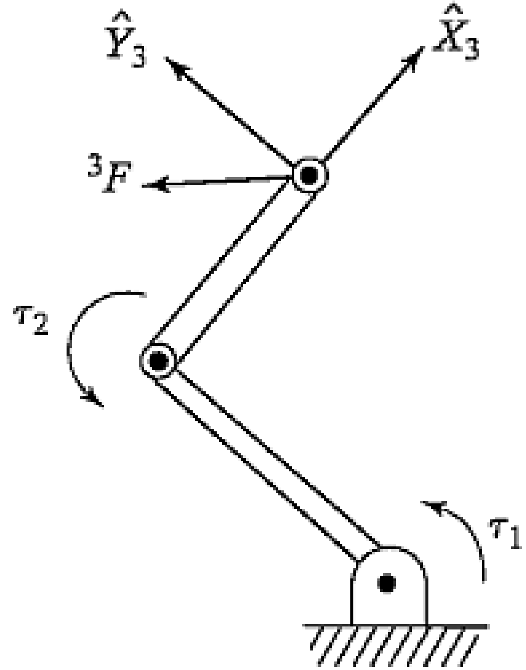
Example

- The two-link manipulator is applying a force vector ${}^3F$ with its end-effector. (Consider this force to be acting at the origin of {3}.) Find the required joint torques as a function of configuration and of the applied force.

Using our results

$$ {}^i f_i = {}^{i}_{i+1}R \, {}^{i+1} f_{i+1}, $$

$$ {}^i n_i = {}^{i}_{i+1}R \, {}^{i+1} n_{i+1} + {}^i P_{i+1} \times {}^i f_i . $$

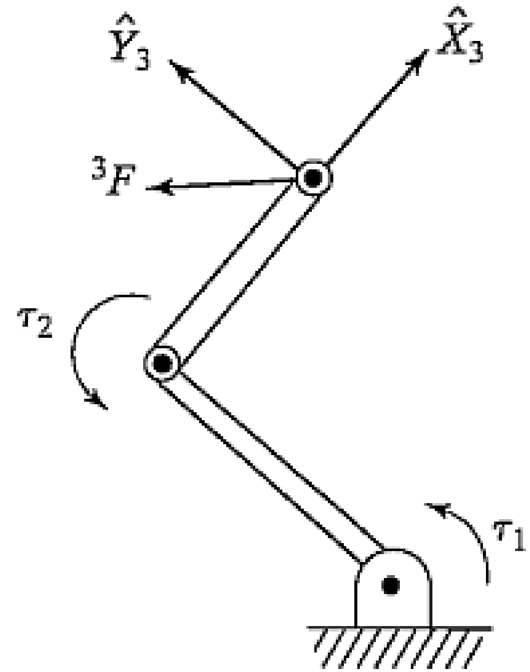


Example

Using our results

$$ {}^{i}f_i = {}^{i}_{i+1}R \, {}^{i+1}f_{i+1}, $$

$$ {}^{i}n_i = {}^{i}_{i+1}R \, {}^{i+1}n_{i+1} + {}^{i}P_{i+1} \times {}^{i}f_i. $$



$$ {}^{2}f_2 = \begin{bmatrix} f_x \\ f_y \\ 0 \end{bmatrix} $$

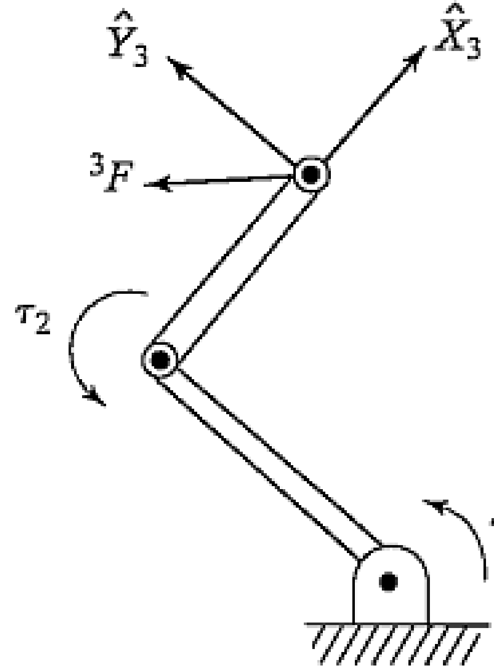
$$ {}^{2}n_2 = l_2 \hat{X}_2 \times \begin{bmatrix} f_x \\ f_y \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ l_2 f_y \end{bmatrix} $$

Example

Using our results

$$ {}^{i}f_i = {}^{i}_{i+1}R \, {}^{i+1}f_{i+1}, $$

$$ {}^{i}n_i = {}^{i}_{i+1}R \, {}^{i+1}n_{i+1} + {}^{i}P_{i+1} \times {}^{i}f_i. $$

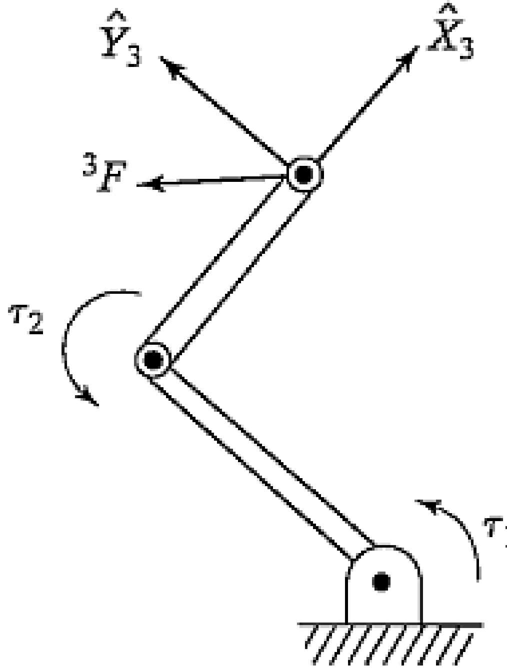


$$ {}^{1}f_1 = \begin{bmatrix} c_2 & -s_2 & 0 \\ s_2 & c_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_x \\ f_y \\ 0 \end{bmatrix} = \begin{bmatrix} c_2 f_x - s_2 f_y \\ s_2 f_x + c_2 f_y \\ 0 \end{bmatrix} $$

$$ {}^{1}n_1 = \begin{bmatrix} 0 \\ 0 \\ l_2 f_y \end{bmatrix} + l_1 \hat{X}_1 \times {}^{1}f_1 = \begin{bmatrix} 0 \\ 0 \\ l_1 s_2 f_x + l_1 c_2 f_y + l_2 f_y \end{bmatrix} $$

Example

Using our results



$$\tau_i = {}^i n_i^T \, {}^i\hat{Z}_i .$$

$$\tau_1 = l_1 s_2 f_x + (l_2 + l_1 c_2) f_y,$$

$$\tau_2 = l_2 f_y .$$

$$\tau = \begin{bmatrix} l_1 s_2 & l_2 + l_1 c_2 \\ 0 & l_2 \end{bmatrix} \begin{bmatrix} f_x \\ f_y \end{bmatrix}$$

Note that this matrix is transpose of Jacobian we found earlier

$${}^3J(\Theta) = \begin{bmatrix} l_1 s_2 & 0 \\ l_1 c_2 + l_2 & l_2 \end{bmatrix}$$

Jacobians in the Force Domain

- We have found joint torques that will exactly balance forces at the hand in the static situation.

- When forces act on a mechanism, work (in the technical sense) is done if the mechanism moves through a displacement.

- **Work** is defined as a force acting through a distance and is a scalar with units of energy.

Jacobians in the Force Domain

- If we assume a infinitesimal displacement for our static case (relaxing stringent static definition). we can equate the work done in Cartesian terms with the work done in joint-space terms.

$$\mathcal{F} \cdot \delta\chi = \tau \cdot \delta\Theta$$

where $\mathcal{F}$ is a 6×1 Cartesian force-moment vector acting at the end-effector, $\delta\chi$ is a 6×1 infinitesimal Cartesian displacement of the end-effector, τ is a 6×1 vector of torques at the joints, and $\delta\Theta$ is a 6×1 vector of infinitesimal joint displacements.

Jacobians in the Force Domain

$$\mathcal{F} \cdot \delta\chi = \tau \cdot \delta\Theta$$

$$\mathcal{F}^T \delta\chi = \tau^T \delta\Theta.$$

The definition of the Jacobian is

$$\delta\chi = J\delta\Theta,$$

so we may write

$$\mathcal{F}^T J\delta\theta = \tau^T \delta\Theta,$$

which must hold for all $\delta\Theta$; hence, we have

$$\mathcal{F}^T J = \tau^T.$$

Transposing both sides yields this result:

$$\tau = J^T \mathcal{F}.$$

Hence, the Jacobian transpose maps Cartesian forces acting at the hand into equivalent joint torques.

Jacobians in the Force Domain

- When the Jacobian is written with respect to frame {0}, then force vectors written in {0} can be transformed, as is made clear by the following notation

$$\tau = {}^{0}J^{T}\,{}^{0}\mathcal{F}.$$

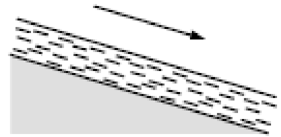
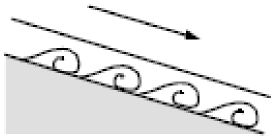
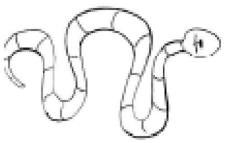
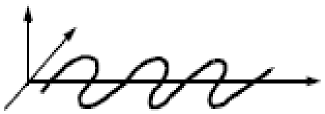
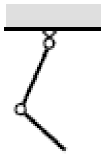
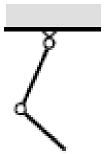
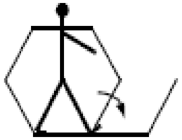
- When the Jacobian loses full rank, there are certain directions in which the end-effector cannot exert static forces even if desired. Thus, singularities manifest themselves in the force domain as well as in the position domain.

LOCOMOTION

Walking, running, hopping, swimming, tensegrity, …

Locomotion

Locomotion principals 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

- Locomotion mechanisms enable the robot to move unbounded throughout its environment.

- Concepts found in nature
  - difficult to imitate technically

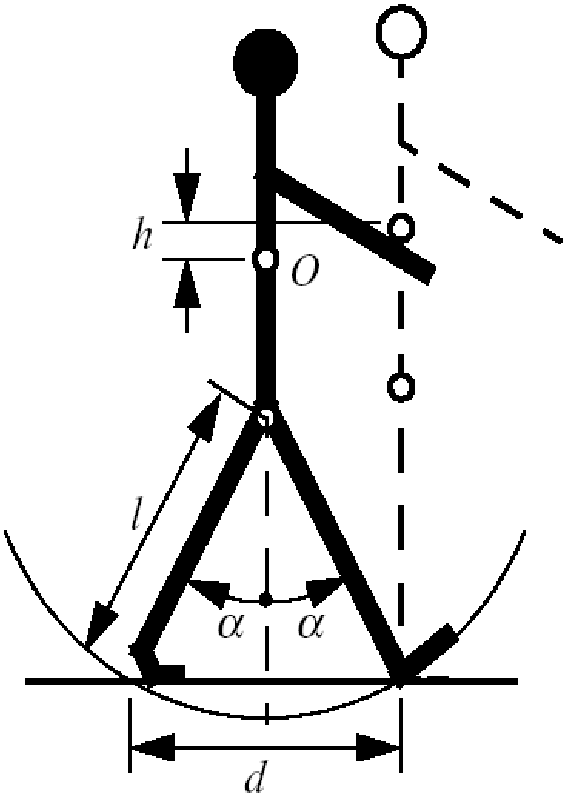
- Most technical systems use wheels

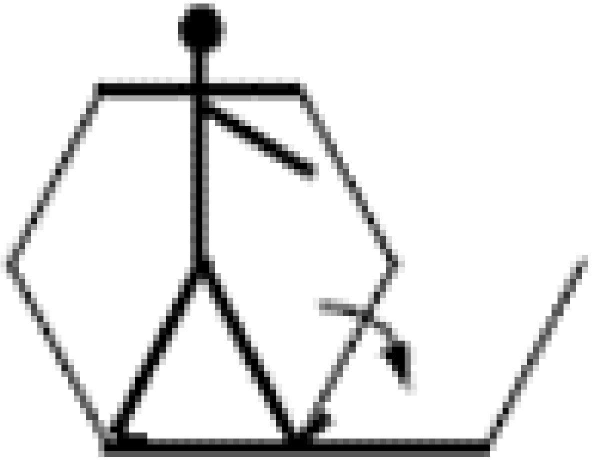
- Rolling is most efficient, but not found in nature
  - nature never invented the wheel!

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

Locomotion

- The movement of a walking biped is ***close to rolling***

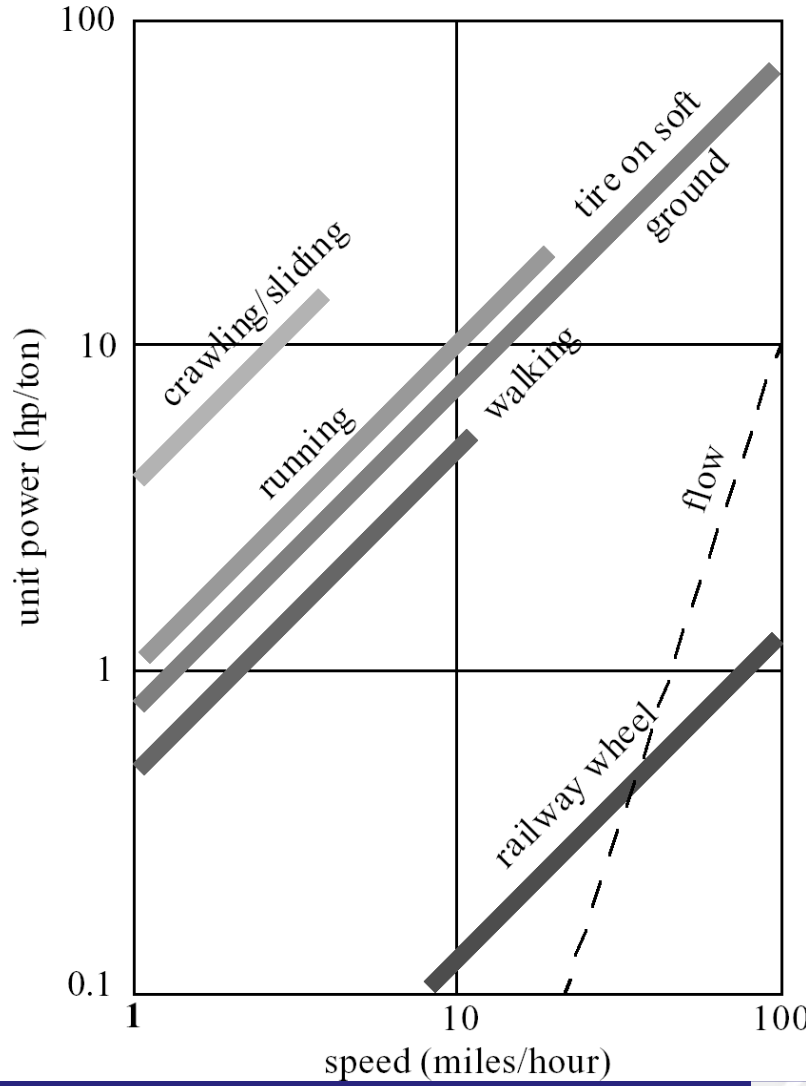




- Biped walking mechanism
  1. not too far from real rolling.
  2. rolling of a polygon with side length equal to the length of the step.
  3. the smaller the step gets, the more the polygon tends to a circle (wheel).

Locomotion

- Walking or Rolling?
  - number of actuators
  - structural complexity
  - control expense
  - energy efficient
    - terrain (flat ground, soft ground, climbing...)
  - movement of the involved masses
    - walking / running includes up down movement of CoG
    - some extra losses



Locomotion

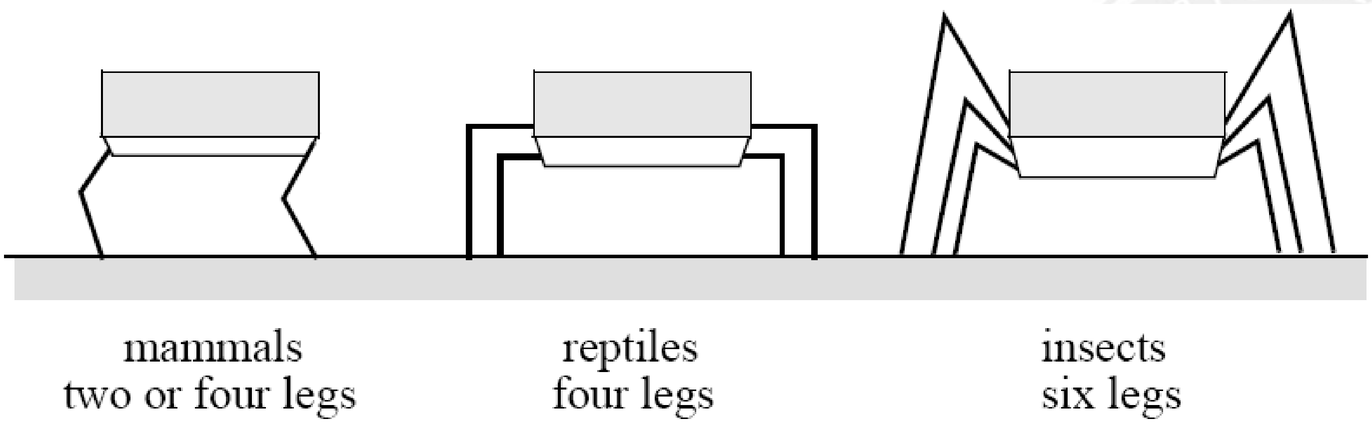
- Characterization of locomotion concepts
- Locomotion
  - physical interaction between the vehicle and its environment.
- Locomotion is concerned with *interaction forces*, and the *mechanisms* and *actuators* that generate them.
- The most important issues in locomotion are:

- stability
  - number of contact points
  - center 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)

- The fewer legs the more complicated becomes locomotion
  - Stability - at least three legs are required for static stability (stability when stationary)
- During walking some legs are lifted
  - thus loosing stability?
- For static walking, at least 3 legs are required
  - babies have to learn for quite a while until they are able to stand or even walk on the two legs while reptiles and mammals need less time.

Static Walk: Walking with at least three legs in contact with ground to achieve static stability during walk.



Mobile Robots with Legs (Walking Machines)

- A minimum of two **DOF** is required to move a leg forward
  - a *lift* and a *swing* motion.
  - sliding free motion in more then only one direction not possible

- Three DOF for each leg in most cases (3rd one being the knee joint)

- Fourth DOF for the ankle joint
  - might improve walking
  - however, additional joint (DOF) increase the complexity of the design, increase the leg mass and especially of the locomotion control.

Number of Joints of Each Leg (DOF: degrees of freedom)

Mobile Robots with Legs (Walking Machines)

- The number of distinct event sequences (gaits)
- The gait is characterized as the distinct 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:

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

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

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

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

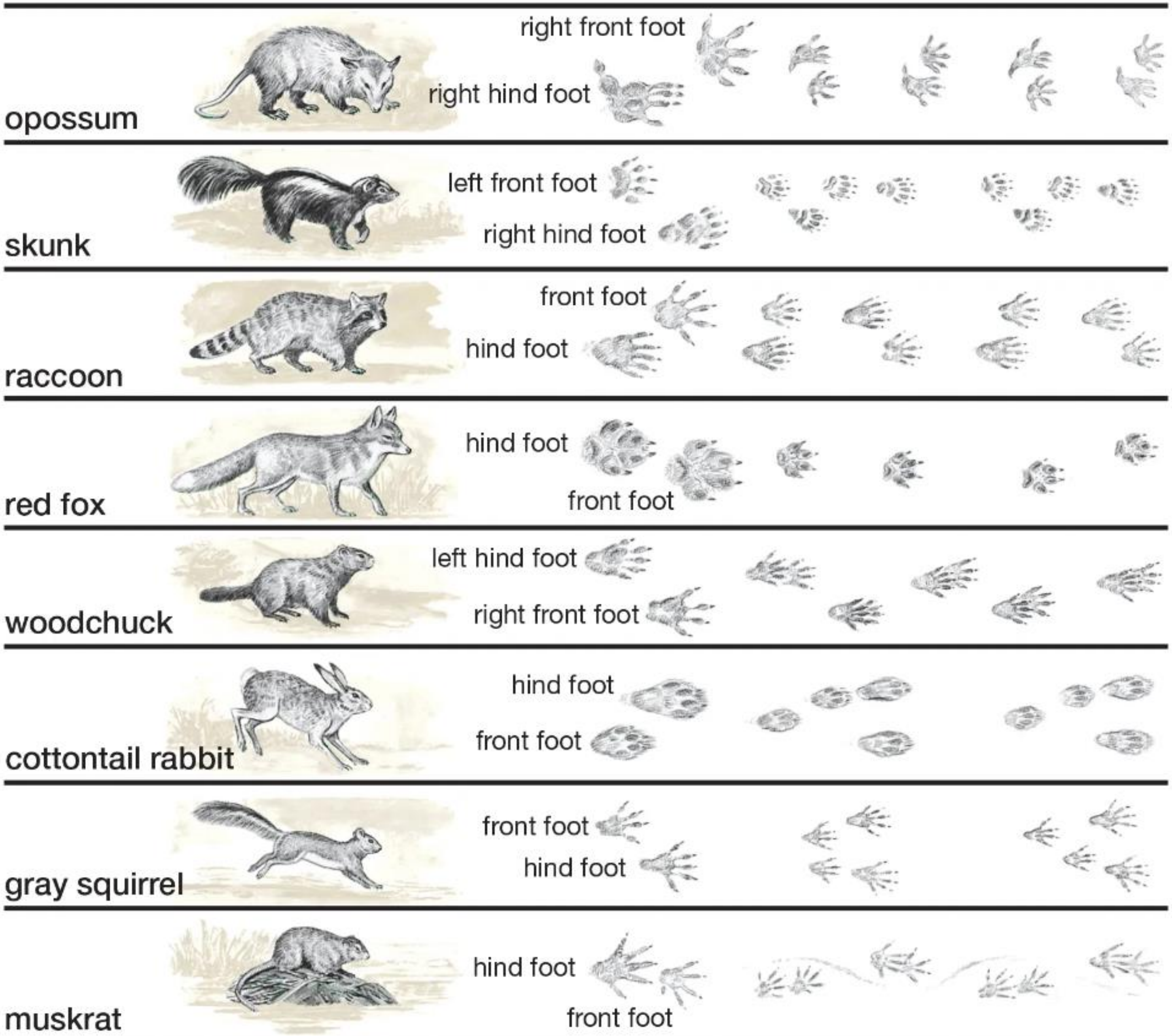
$$N = 11! = 39'916'800$$

The number of distinct event sequences for biped:

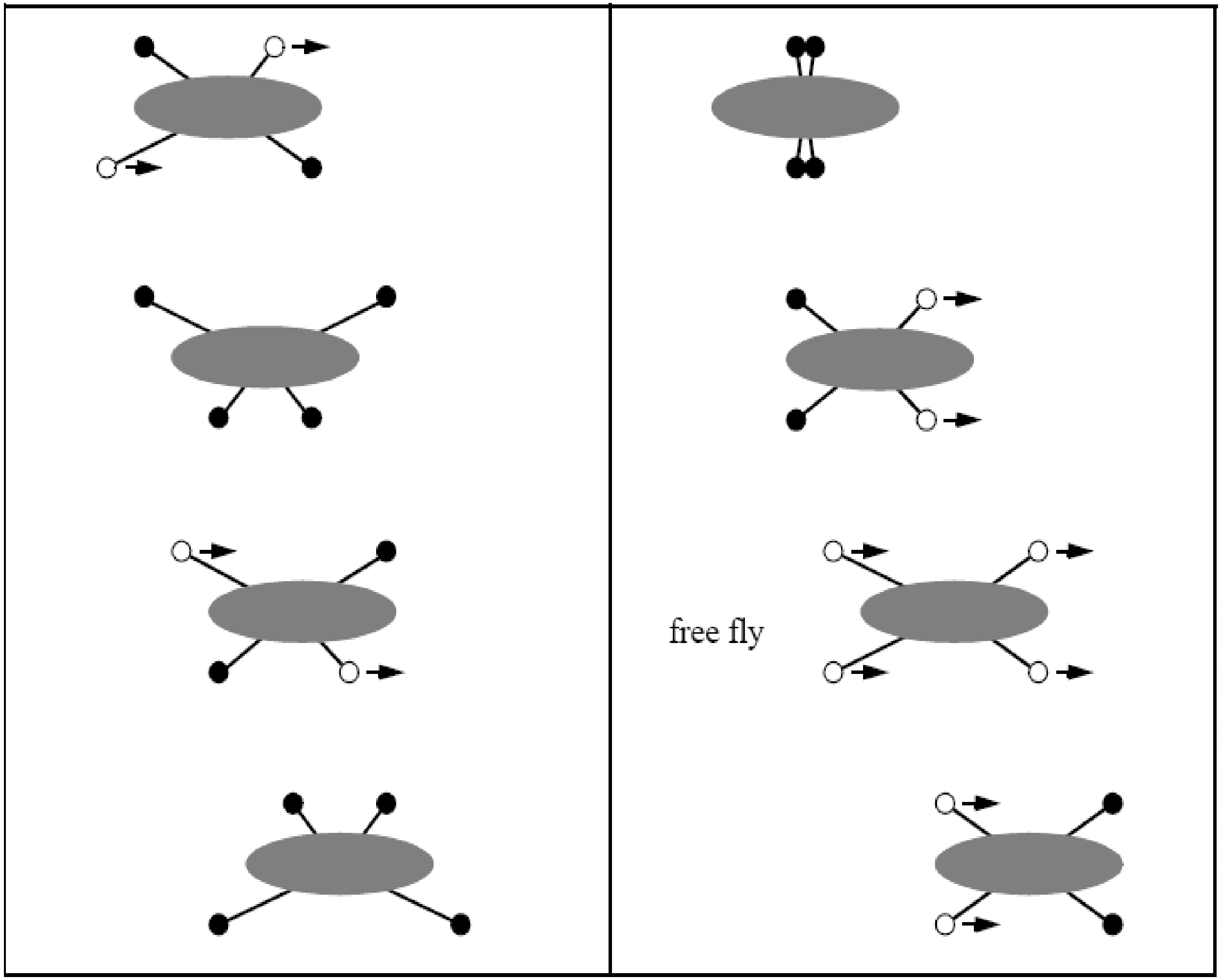
● *Leg down*
○ *Leg up*

- With two legs (biped) one can have four different states
  - 1) Both legs down ●/●
  - 2) Right leg down, left leg up ○/●
  - 3) Right leg up, left leg down ●/○
  - 4) Both leg up ○/○
- A distinct event sequence can be considered as a change from one state to another and back. $N = (2k-1)! = 6$
- So we have the following distinct event sequences (change of states) for a biped:

1 -> 2 -> 1	●/● ○/● ●/●	→	*turning on right leg*
1 -> 3 -> 1	●/● ●/○ ●/●	→	*turning on left leg*
1 -> 4 -> 1	●/● ○/○ ●/●	→	*hopping with two legs*
2 -> 3 -> 2	○/● ●/○ ○/●	→	*walking running*
2 -> 4 -> 2	○/● ○/○ ○/●	→	*hopping right leg*
3 -> 4 -> 3	●/○ ○/○ ●/○	→	*hopping left leg*

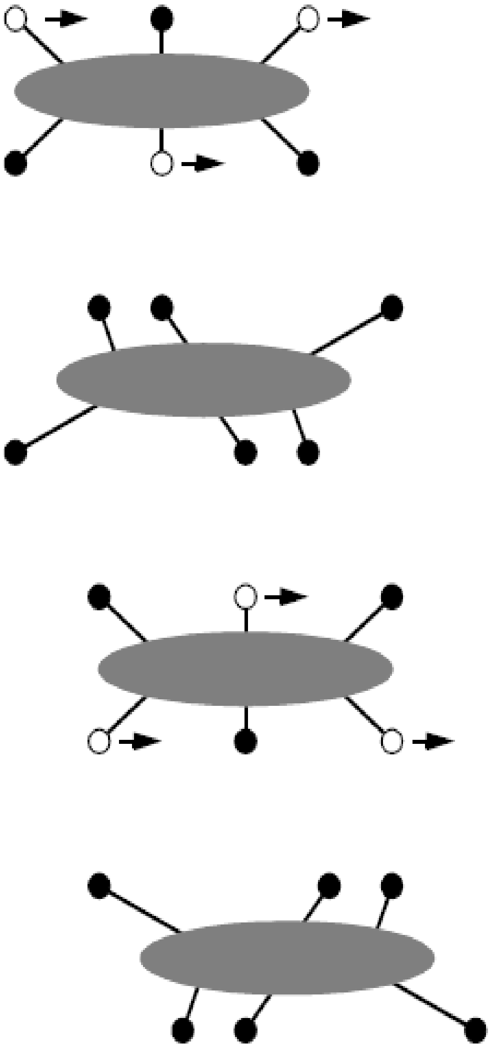

opossum
right front foot
right hind foot
skunk
left front foot
right hind foot
raccoon
front foot
hind foot
red fox
hind foot
front foot
woodchuck
left hind foot
right front foot
cottontail rabbit
hind foot
front foot
gray squirrel
front foot
hind foot
muskrat
hind foot
front foot

Most obvious gaits (4 legs)



Changeover walking galloping(horse)

Most obvious gaits (6 legs)

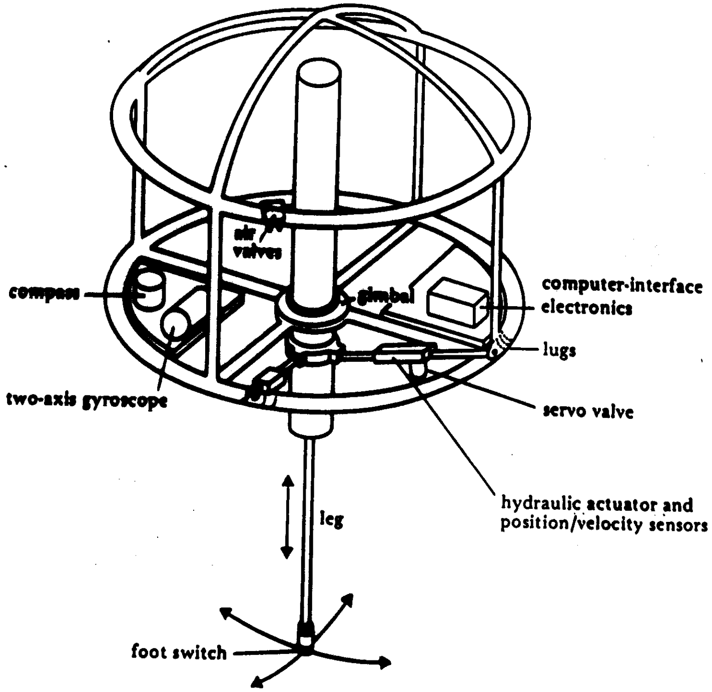


Examples of Walking Machines (one leg)

- No industrial applications to date, but a popular research field
- For an excellent overview please see:

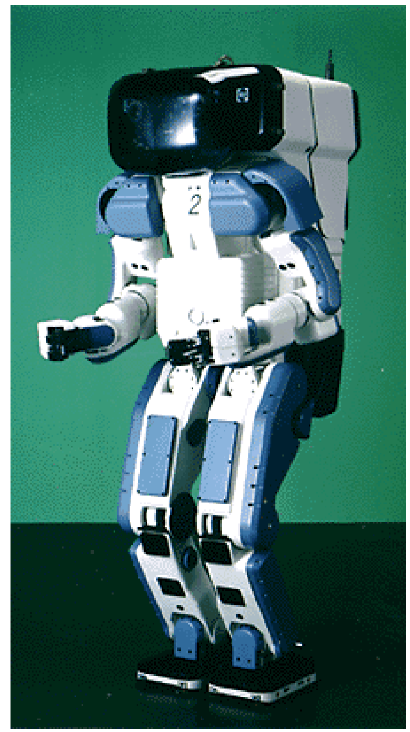
  http://www.uwe.ac.uk/clawar/

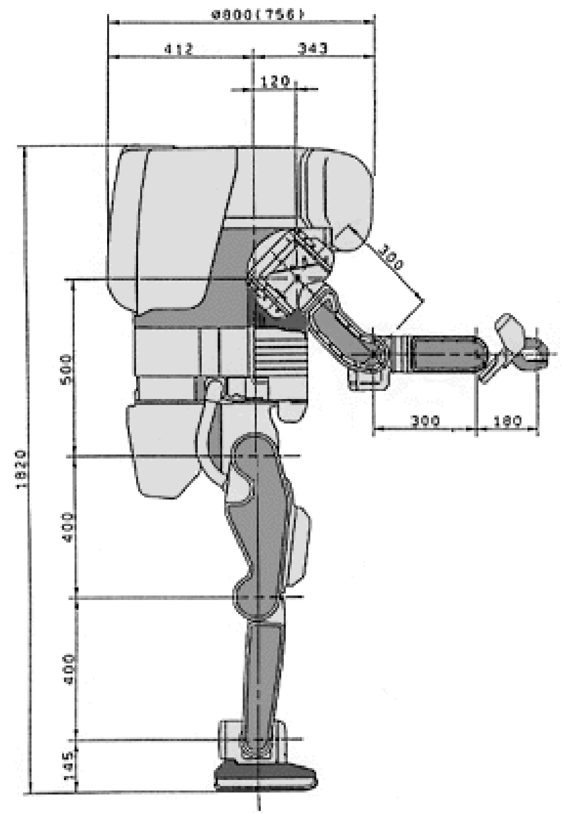
The Hopping Machine at MIT



Humanoid Robots (biped)

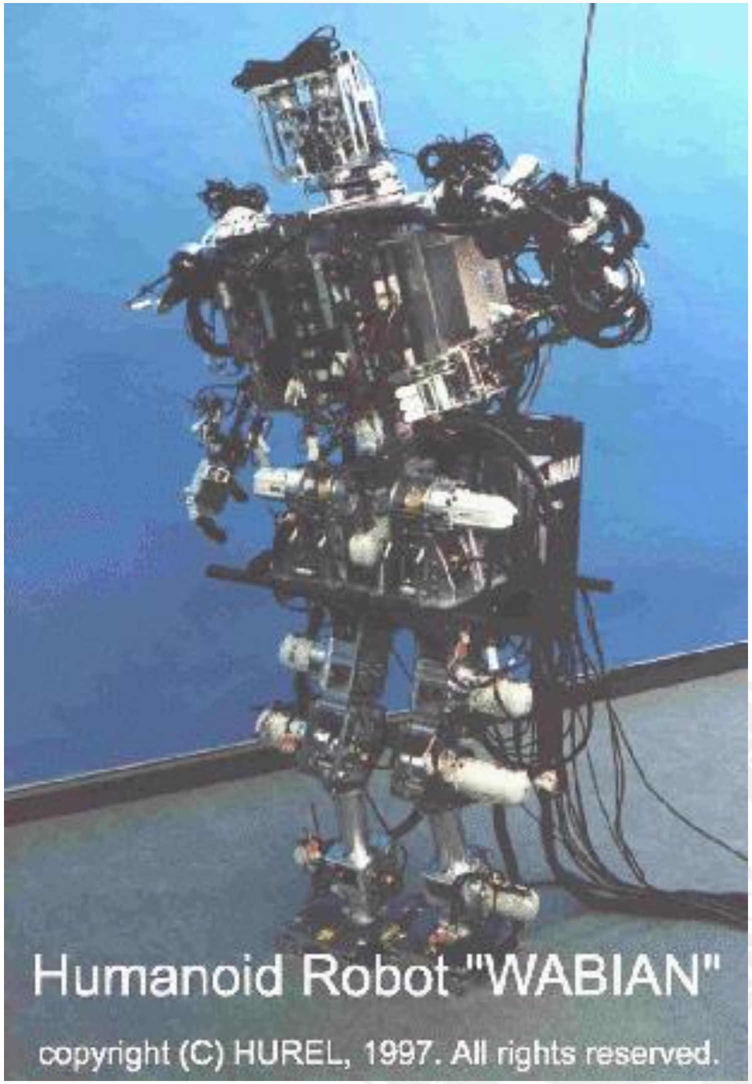
- P2 from Honda, Japan
  - Maximum Speed: 2 km/h
  - Autonomy: 15 min
  - Weight: 210 kg
  - Height: 1.82 m
  - Leg DOF: 2 × 6
  - Arm DOF: 2 × 7





Humanoid Robots

- Wabian build at
  Waseda University in Japan
    - Weight:107 kg
    - Height: 1.66 m
    - DOF in total: **43**
- Application:
  Human Robot Interaction



Humanoid Robots

- NAO robot built by Aldebaran Robotics

Moving : 25 degrees of freedom and a humanoid shape that enable him to move and adapt to the world around him. His inertial unit enables him to maintain his balance and to know whether he is standing up or lying down.

Feeling : The numerous sensors in his head, hands and feet, as well as his sonars, enable him to perceive his environment and get his bearings.

Hearing and speaking : With his 4 directional microphones and loudspeakers, NAO interacts with humans in a completely natural manner, by listening and speaking.

Humanoid Robots

- NAO robot built by Aldebaran Robotics

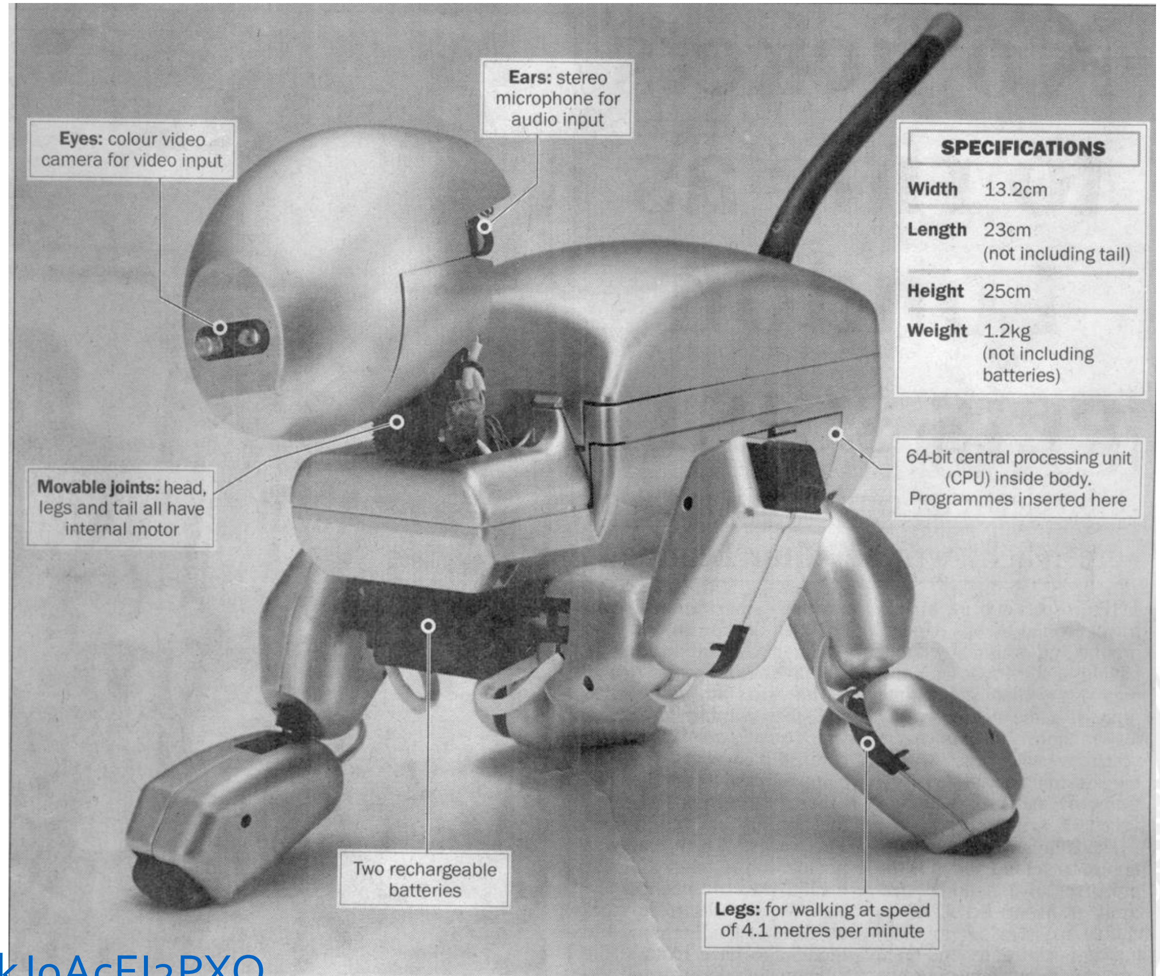
Seeing : NAO is equipped with two cameras that film his environment in high resolution, helping him to recognize shapes and objects.

Connecting : To access the Internet autonomously, NAO is able to use a range of different connection modes (WiFi, Ethernet).

Thinking : We can't really talk about "Artificial Intelligence" with NAO, but the robots are already able to reproduce human behaviour.

Walking Robots with Four Legs (Quadruped)

- Artificial Dog Aibo from Sony, Japan

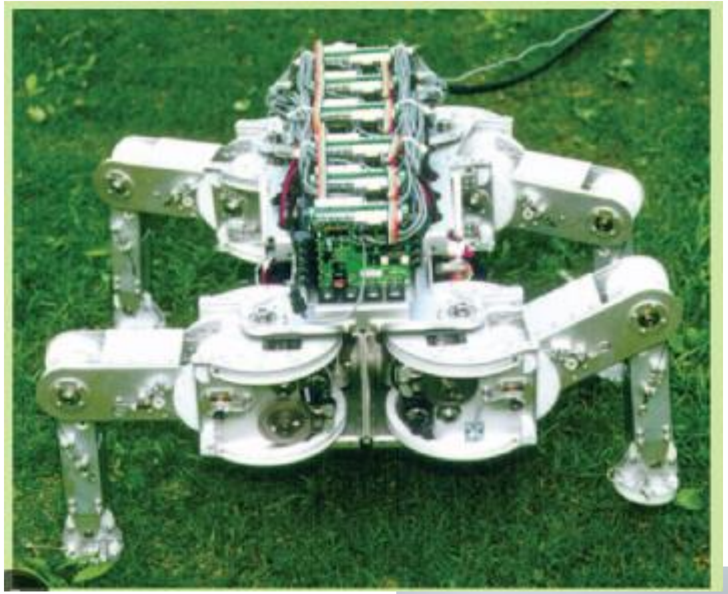


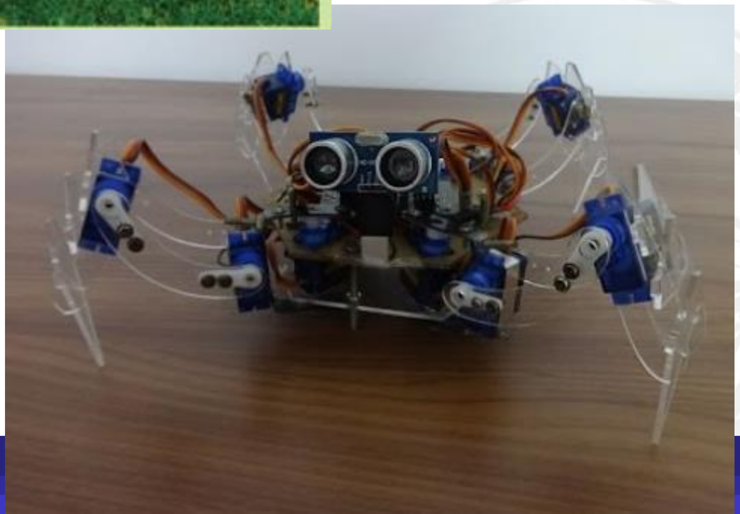
Sony's new computer canine will chase a ball or sit when asked, but cleaning up will be a thing of the past

https://www.youtube.com/watch?v=kJoAcEI2PXQ

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)

- MIT Cheetah robot

- https://www.youtube.com/watch?v=-BqNl3AtPVw

- https://www.youtube.com/watch?v=_luhn7TLfWU

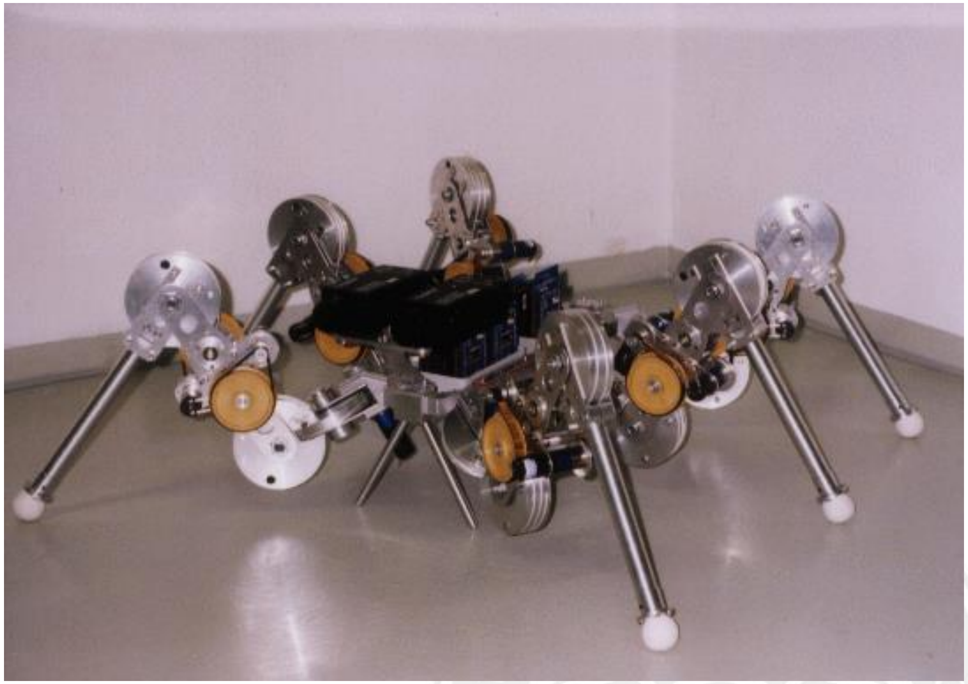
Walking Robots with Six Legs (Hexapod)

- Most popular because static stable walking possible

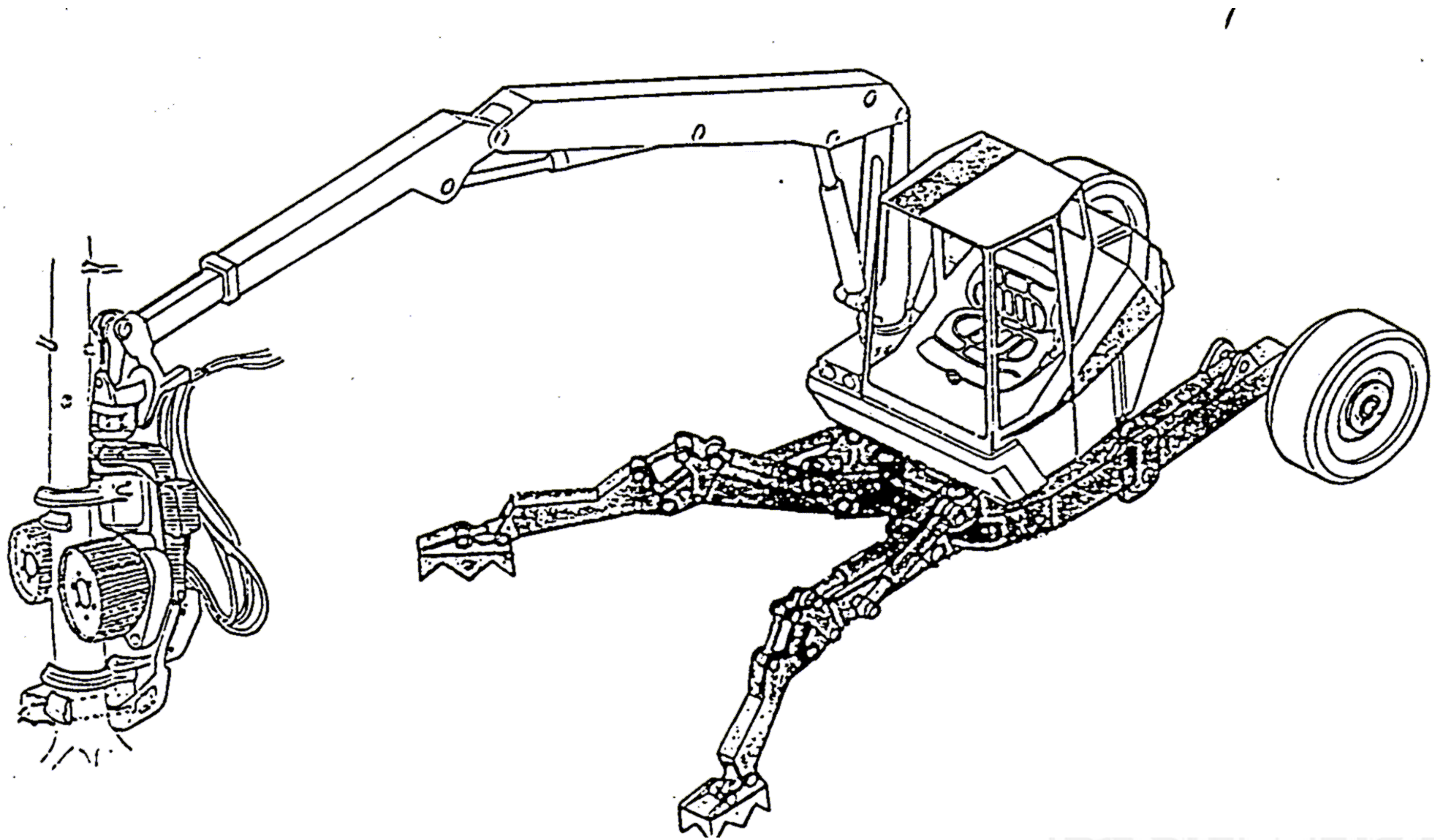
- The human guided hexapod of Ohio State University
  - Maximum Speed: 2.3 m/s
  - Weight: 3.2 t
  - Height: 3 m
  - Length: 5.2 m
  - No. of legs: 6
  - DOF in total: $6 * 3$

Walking Robots with Six Legs (Hexapod)

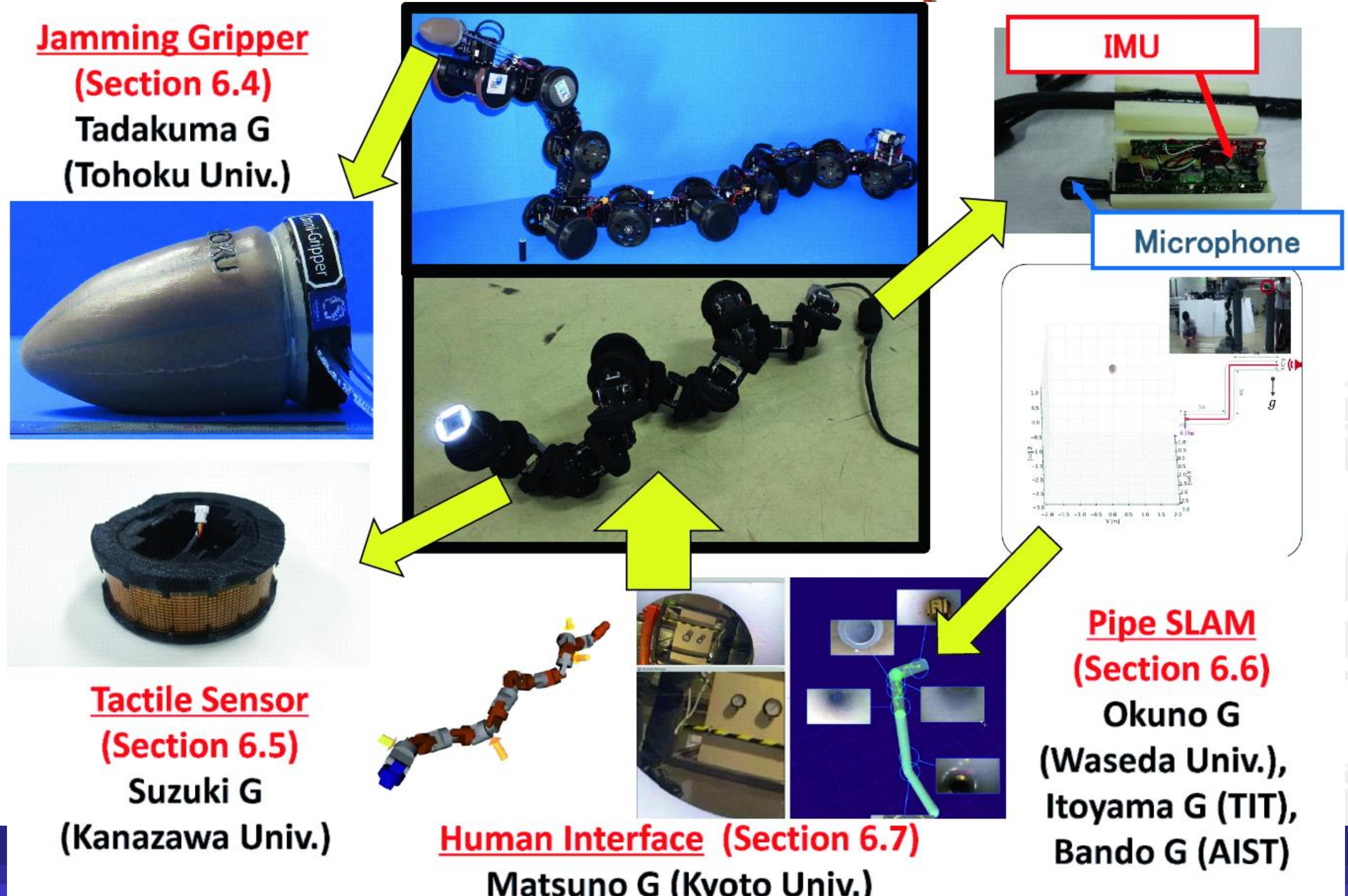
- Lauron II, University of Karlsruhe
  - Maximum Speed: 0.5 m/s
  - Weight: 6 kg
  - Height: 0.3 m
  - Length: 0.7 m
  - No. of legs: 6
  - DOF in total: $6 * 3$
  - Power Consumption: 10 W



RoboTrac, a hybrid wheel-leg vehicle



Spiral Snake Robot



Mobile Robots with Wheels

- Wheels are the most appropriate solution for most applications

- Three wheels are sufficient to guarantee stability

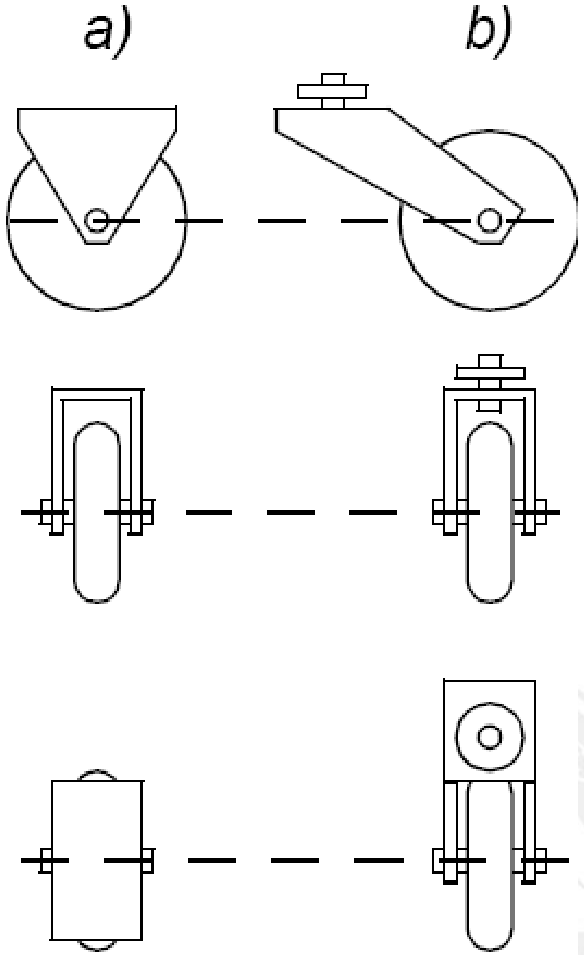
- With more than three wheels an appropriate suspension is required

- Selection of wheels depends on the application

The Four Basic Wheel Types

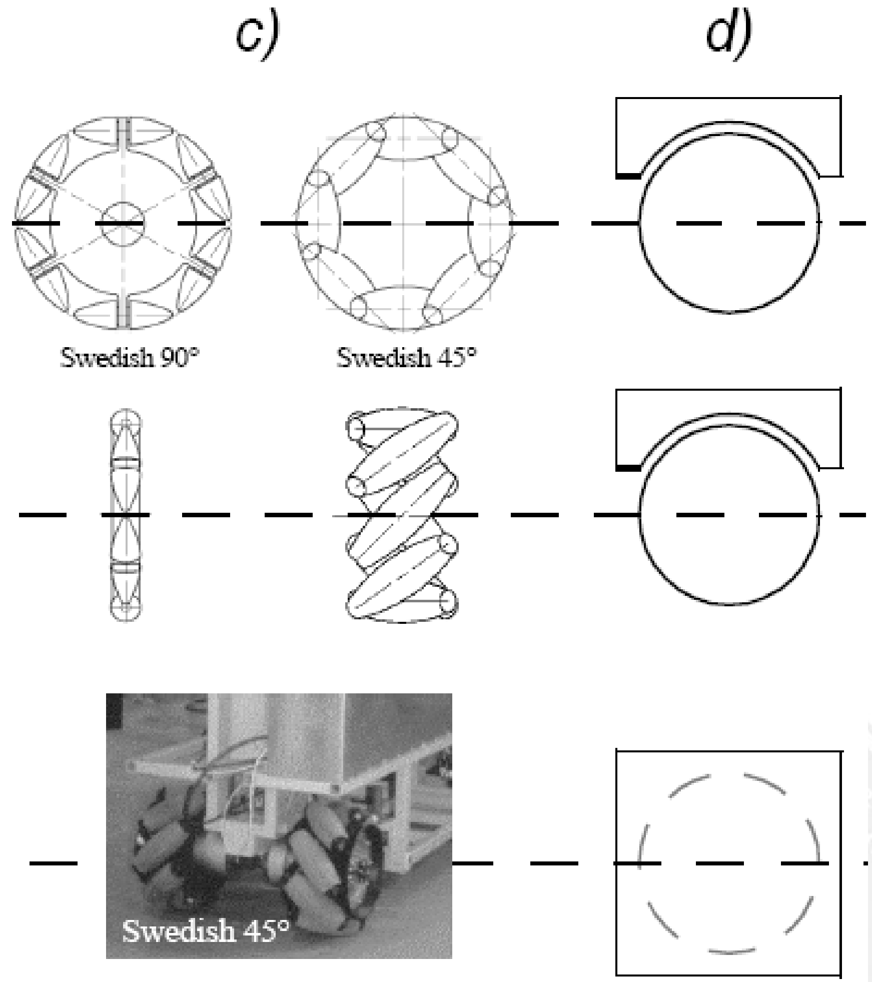
a) Standard wheel: Two degrees of freedom; rotation around the (motorized) wheel axle and the contact point

b) Castor wheel: Two degrees of freedom; rotation around the wheel axle, and an offset steering joint.



The Four Basic Wheel Types

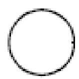
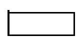
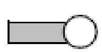
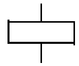
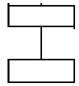
c) Swedish wheel: Three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers and around the contact point



d) Ball or spherical wheel: Suspension technically not solved

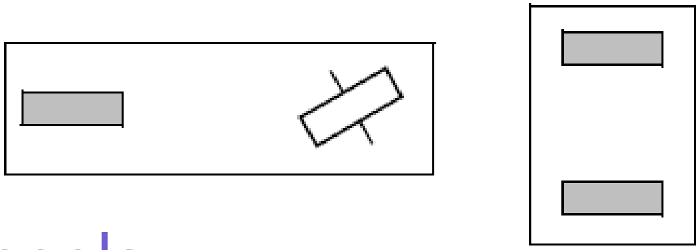
Different Arrangements of Wheels I

- Key Trade-off while selecting a specific type of wheel
  - Stability, maneuverability, controllability
- Legends

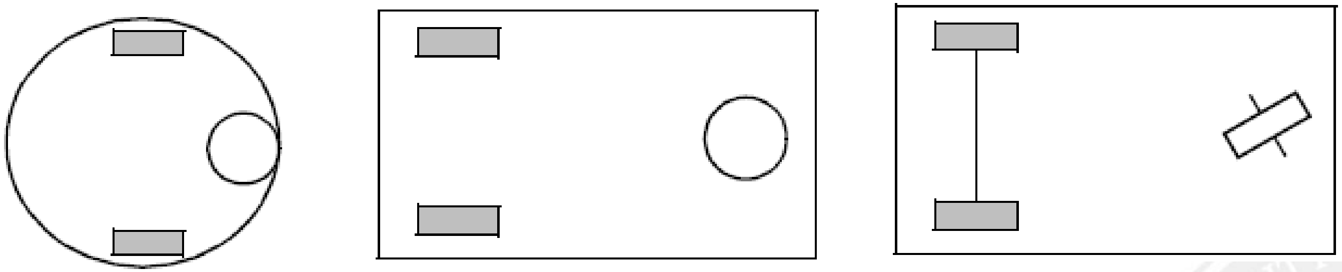
Icons for the each wheel type are as follows:	
	unpowered omnidirectional wheel (spherical, castor, Swedish);
	motorized Swedish wheel (Stanford wheel);
	unpowered standard wheel;
	motorized standard wheel;
	motorized and steered castor wheel;
	steered standard wheel;
	connected wheels.

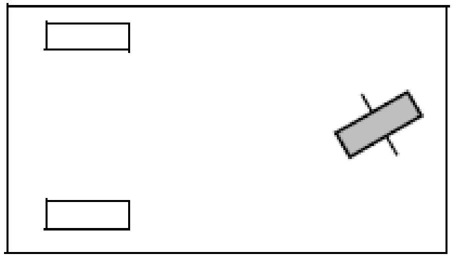
Different Arrangements of Wheels I

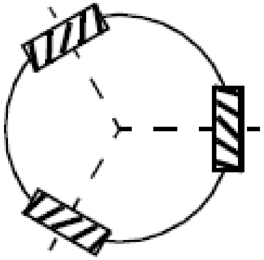
- Two wheels



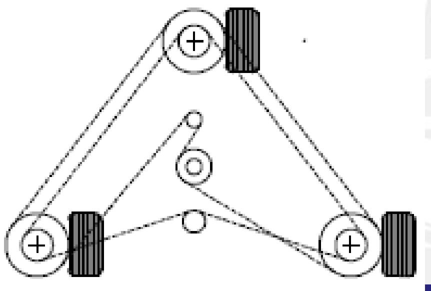
- Three wheels







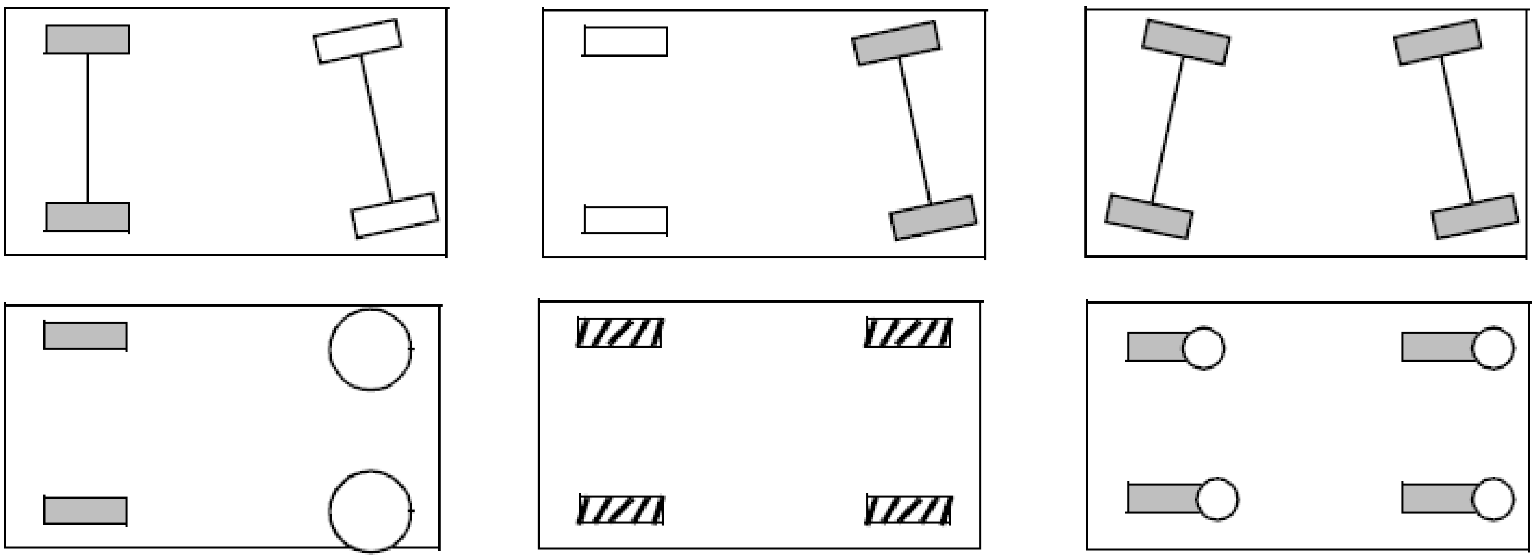
Omnidirectional Drive



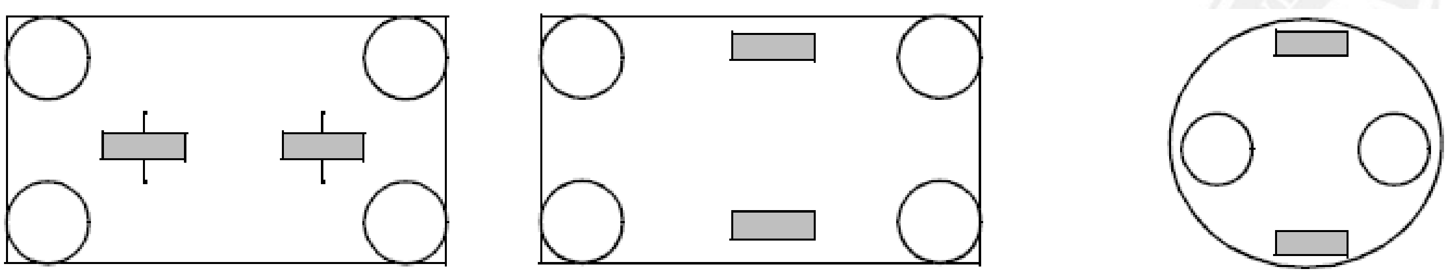
Synchro Drive

Different Arrangements of Wheels II

- Four wheels



- Six wheels

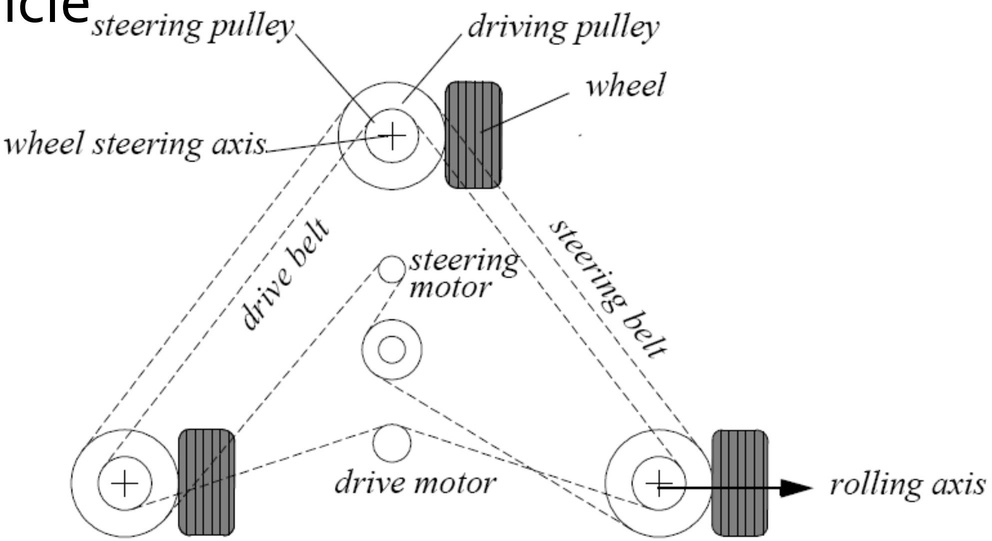


Cye, a Two Wheel Differential Drive Robot

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

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 same

- It is therefore not possible to control the orientation of the robot frame.

LEONARDO (LEgs ONboARD drOne)

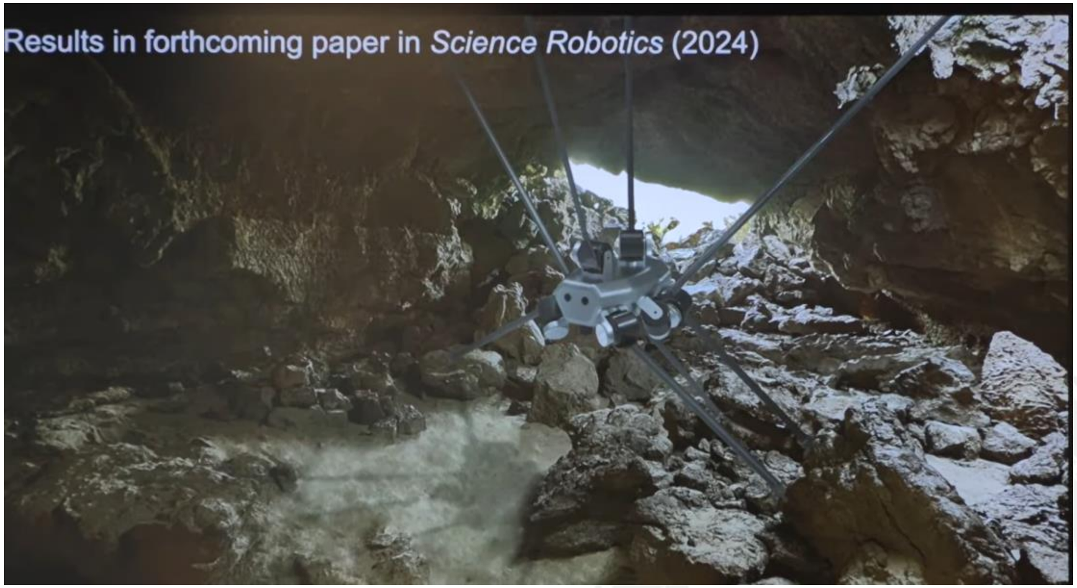
- Robot that can walk, fly, skateboard, slacklines
- California Institute of Technology (Caltech)

https://www.youtube.com/watch?v=H1_OpWiyijU

ReachBOT

- http://bdml.stanford.edu/Main/ReachBot

- Body mass/shape
- Leg length
- Sensors adjustment and grasping
- Booms/cables



https://www.youtube.com/watch?v=y9wIWwnjWDo