Autonomous Mobile Robots

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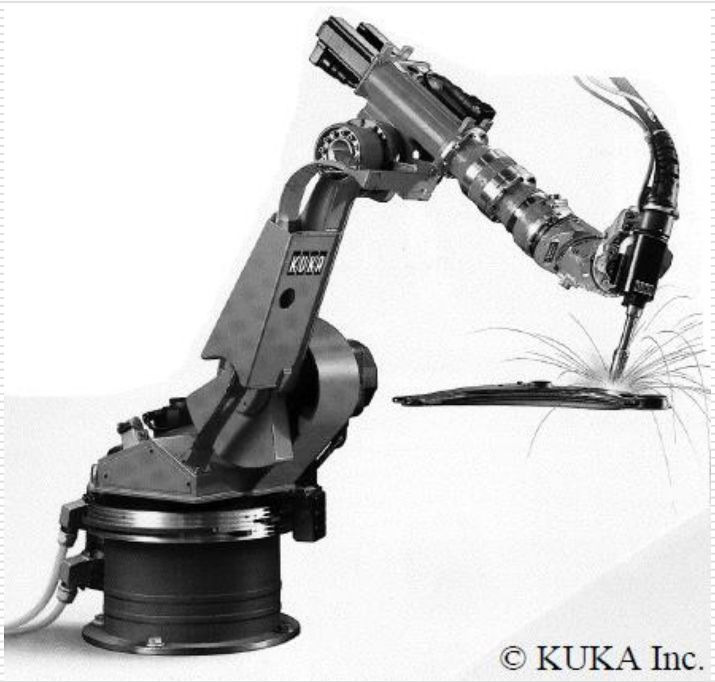
ÇANKAYA ÜNİVERSİTESİ
MEKATRONİK MÜHENDİSLİĞİ BÖLÜMÜ

INTRODUCTION

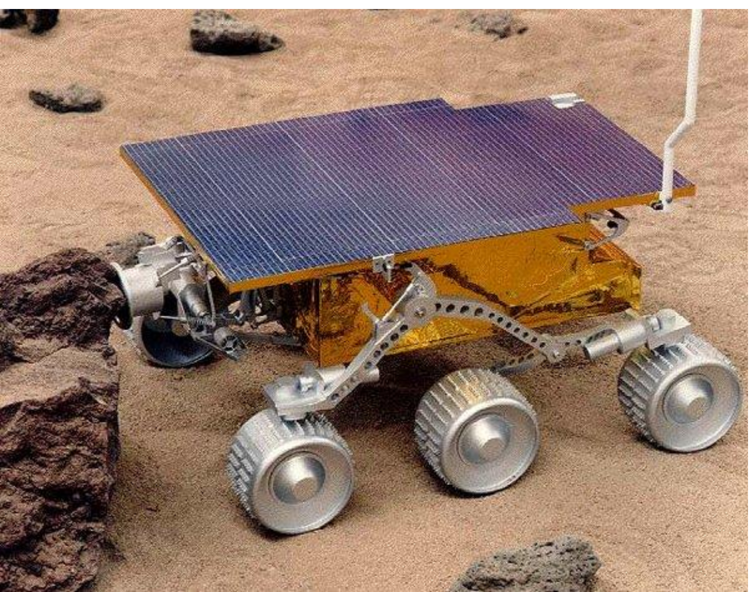
- **Robotics** has achieved its greatest success to date in the world of **industrial manufacturing**.
- Robot arms, or manipulators, comprise a **$ 2 billion** industry.
- **Bolted at its shoulder to a specific position** in the assembly line, the robot arm can move with **great speed and accuracy** to perform **repetitive tasks** such as spot welding and painting



INTRODUCTION

- In the electronics industry, **manipulators** place surface-mounted components with **superhuman precision**, making the portable telephone and laptop computer possible.
- Yet, for all of their successes, these commercial robots suffer from a **fundamental disadvantage**:
- **Lack of mobility**. A fixed manipulator has a **limited range of motion** that depends on where it is bolted down

- **How can a mobile robot move unsupervised (gözetimsiz) through real-world environments to fulfill its tasks**?
- The first challenge is **locomotion** itself. How should a mobile robot move, and what is it about a particular **locomotion mechanism** that makes it superior to alternative locomotion mechanisms?
- Hostile environments such as Mars trigger even more **unusual locomotion mechanisms**.



The mobile robot Sojourner was used during the Pathfinder mission to explore Mars in summer 1997.
It was almost completely teleoperated from Earth. However, some on-board sensors allowed for obstacle detection

- The **low-level complexities of the robot often make it impossible for a human operator** to control its motions directly.
- **The human** performs **localization and cognition activities** but relies on the robot’s control scheme to provide motion control.
- Pluste**first application-driven walking robot**ch developed the.
- It is designed to move wood out of the forest.
- The **leg coordination** is automated, but **navigation** is still done by the human operator on the robot.

Teleoperated Systems

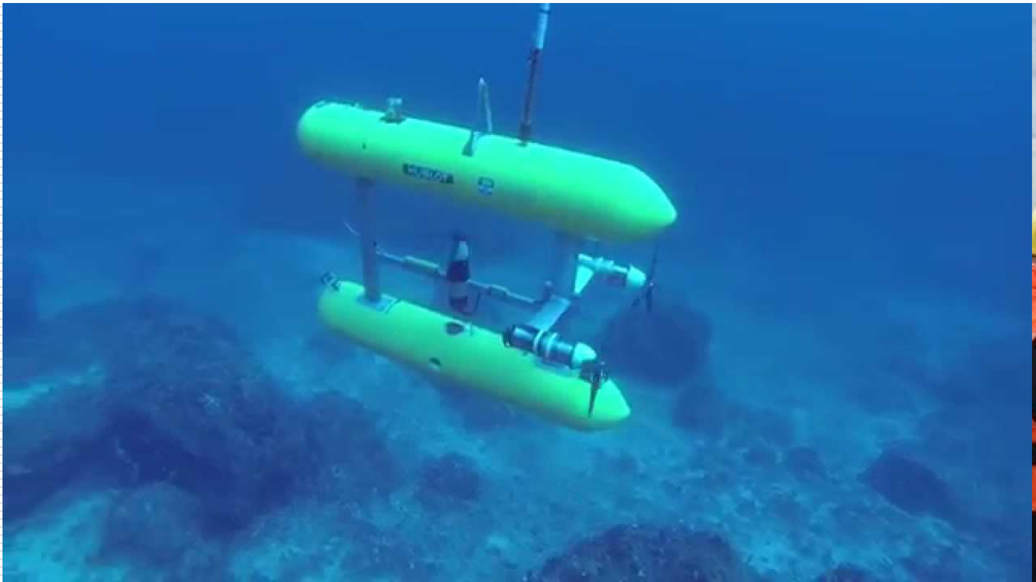
- The MagneBike robot developed by ASL (ETH Zurich) and ALSTOM. MagneBike is a magnetic wheeled robot with high mobility for inspecting complex shaped structures such as ferromagnetic pipes and turbines

Teleoperated Systems

- Picture of Pioneer, a robot designed to explore the Sarcophagus at Chernobyl

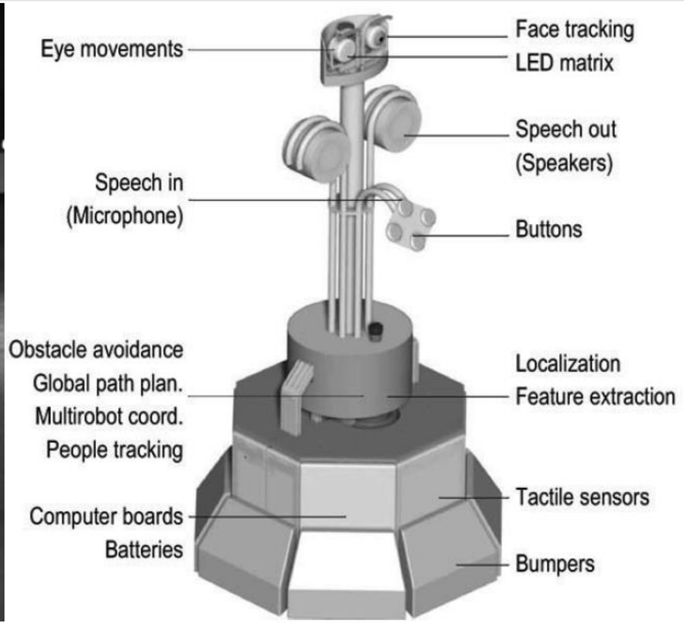
Teleoperated Systems

- The autonomous underwater vehicle (AUV) Sirius controls three propellers to stabilize the robot submarine autonomously in spite of underwater turbulence and water currents while the operator chooses position goals for the submarine to achieve



Autonomous Systems

- Other commercial robots operate not where humans cannot go, but rather share space with humans in human environments.
- These robots are compelling **not for reasons of mobility** but because of their **autonomy**, and so their ability to maintain a sense of position and to navigate without human intervention is paramount.
- Tour-guide robots are able to interact and present exhibitions in an educational way. Ten Roboxes have operated during five months at the Swiss exhibition EXPO.02, meeting hundreds of thousands of visitors.



Autonomous Systems

- Autonomous guided vehicle (AGV) by SWISSLOG used to transport motor blocks from one assembly station to another. It is guided by an electrical wire installed in the floor.

- The autonomous forklift by Esatroll, does not rely on electrical wires, magnetic plots, or reflectors, but rather uses the onboard safety lasers to localize itself with respect to the shape of the environment.

Autonomous Systems

- HELPMATE is a mobile robot used in hospitals for transportation tasks.
- It has various on-board sensors for autonomous navigation in the corridors. The main sensor for localization is a camera looking to the ceiling. It can detect the lamps on the ceiling as references, or landmarks

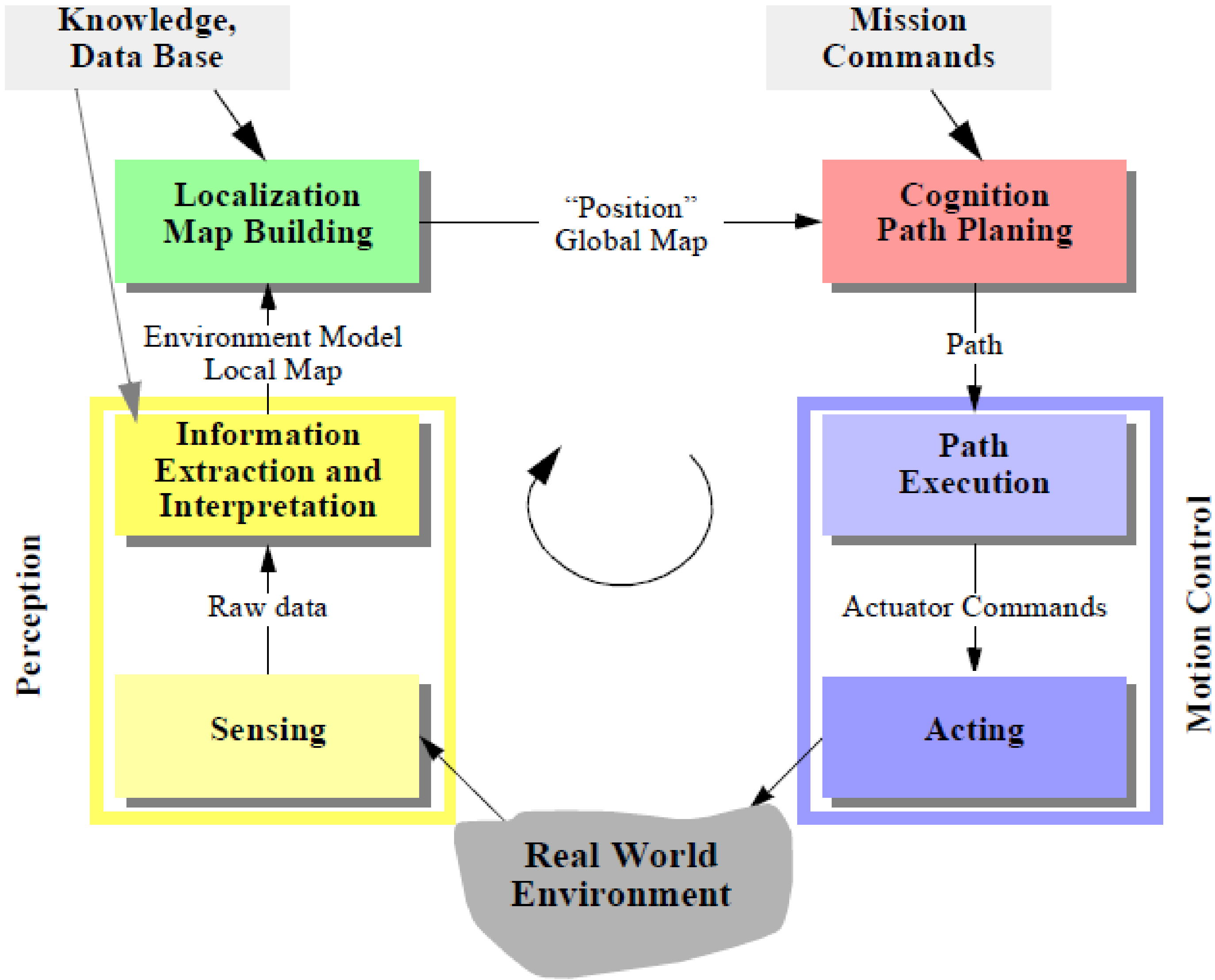
Autonomous Systems

- The Robot40 is a consumer robot developed and sold by Cleanfix for cleaning large gymnasiums. The navigation system of Robo40 is based on a sophisticated sonar and infrared system.
- The RoboCleaner RC 3000 covers badly soiled areas with a special driving strategy until it is really clean. Optical sensors measure the degree of pollution of the aspirated air.

Autonomous Mobile Robot: The Key Questions

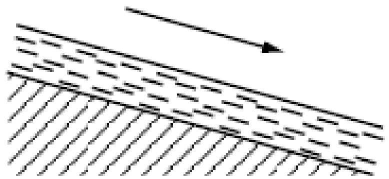
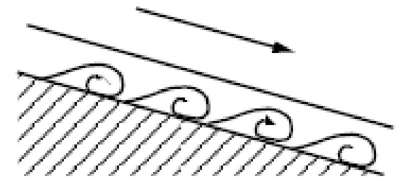
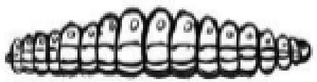
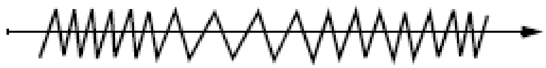
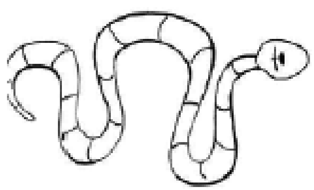
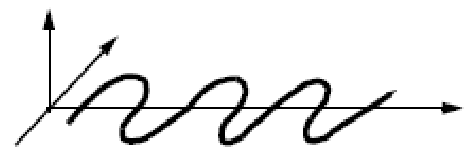
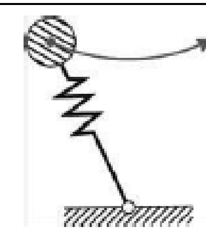
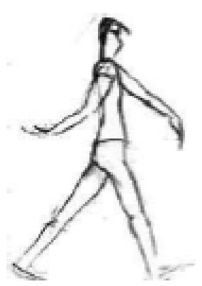
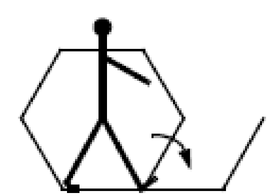
- The three key questions in Mobile Robotics
  - Where am I ?
  - Where am I going ?
  - How do I get there ?
- To answer these questions the robot has to
  - have a model of the environment (given or autonomously built)
  - perceive and analyze the environment
  - find its position/situation within the environment
  - plan and execute the movement

- Mobile robot design involves the integration of many different bodies of knowledge.
- **Locomotion** problems:mechanism and kinematics, dynamics and control theory.
- **Perceptual** systems: signal analysis, computer vision, sensor technologies.
- **Localization** and **navigation**: information theory, artificial intelligence, and probability theory.



Locomotion

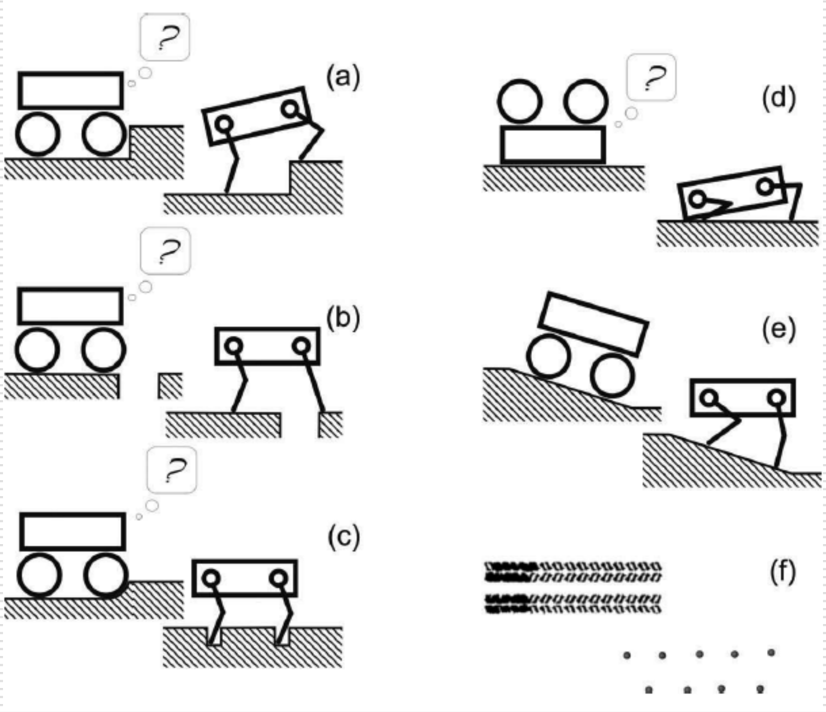
- A mobile robot needs **locomotion mechanisms** that enable it to move unbounded throughout its environment.
- Locomotion is an important aspect of mobile robot design.
- There are research robots that can *walk*, *jump*, *run*, *slide*, *skate*, *swim*, *fly*, *roll*.
- Most of these locomotion mechanisms have been inspired by their biological counterparts.

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	Periodic bouncing on a spring 
Walking 	Loss of kinetic energy	Rolling of a polygon (see figure 2.2) 

- Mobile robots generally locomote either using
  - wheeled mechanisms
  - articulated legs.
- Legged locomotion is complex requiring higher degrees of freedom
- Wheeled locomotion is simple and well suited to flat ground.

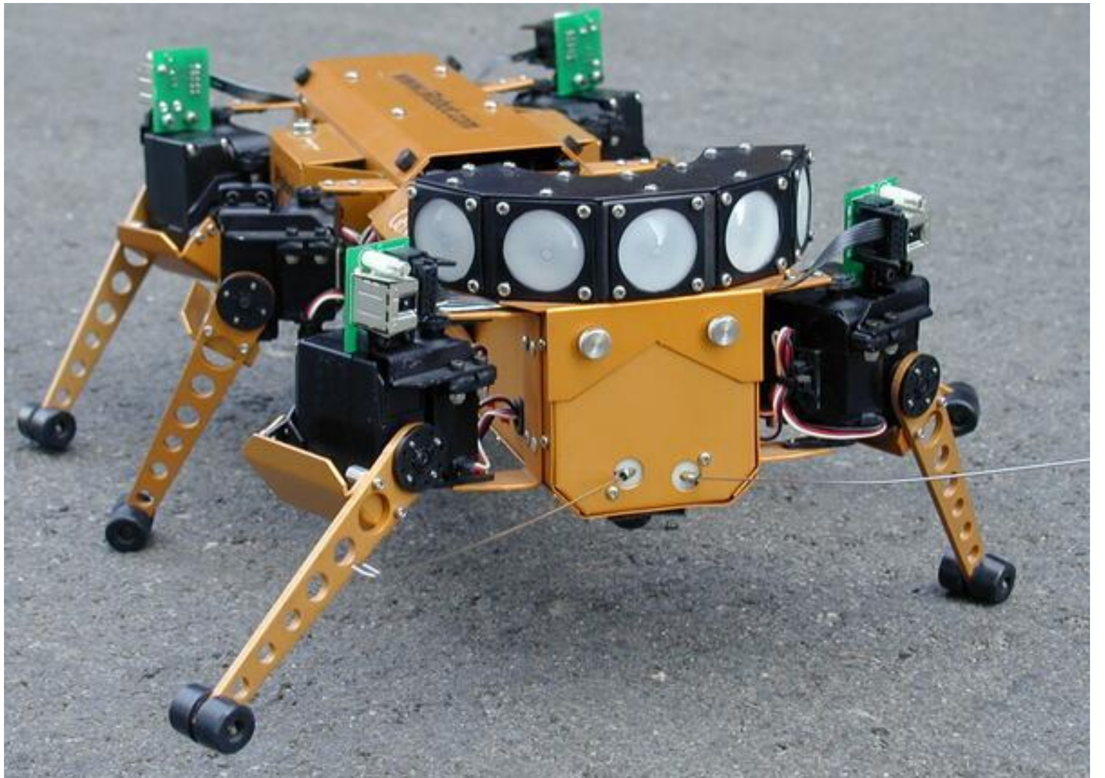
Legged Mobile Robots

- Legged locomotion requires a set of point contacts between the robot and the ground.
- The quality of the ground does not matter.
- Walking robot is capable of crossing a hole or chasm (çukur).



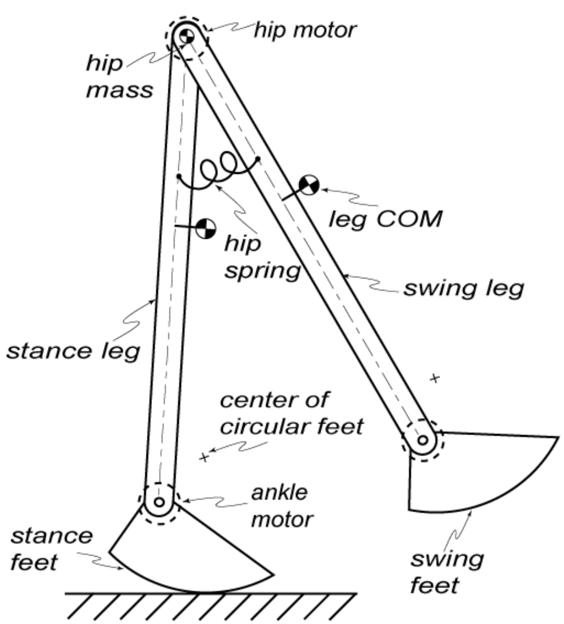
- Genghis is a commercially available hobby robot that has six legs, each of which has two degrees of freedom provided by hobby servos
- Such a robot, which consists only of hip flexion and hip abduction, has less maneuverability in rough terrain but performs quite well on flat ground.
- Because it consists of a straightforward arrangement of servomotors and straight legs, such robots can be readily built by a robot hobbyist

Genghis, (1989)

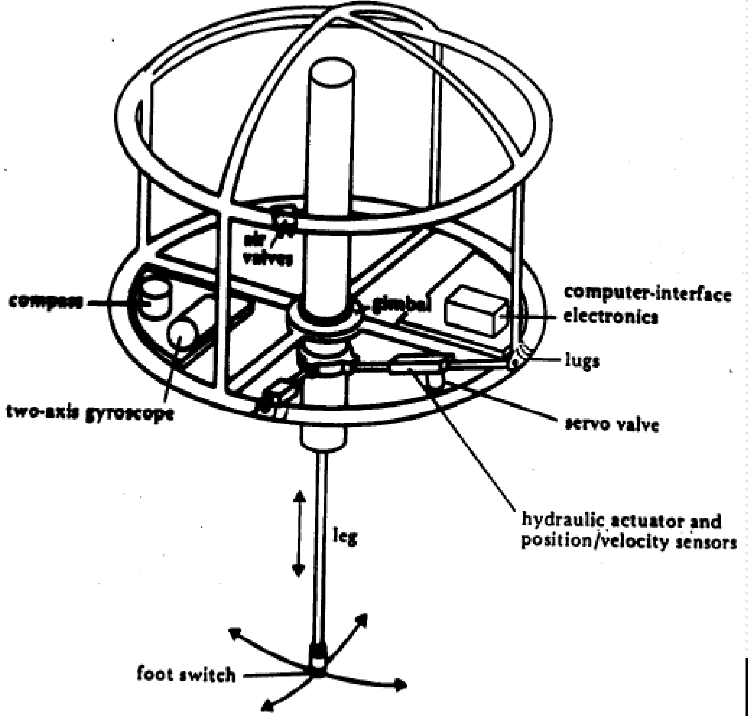


- it is, in fact, possible to build legged robots that **do not have actuation of any kind**.
- Such passive dynamic walkers walk down a shallow incline (which compensates for frictional losses)
- Because no actuators are present, no negative work is performed and **energetic losses due to braking are eliminated**.
- The dynamics of such walkers must be designed to ensure **dynamic stability**.
- The mechanical structure must passively reject small disturbances which would otherwise accumulate over time and eventually cause the robot to fall.

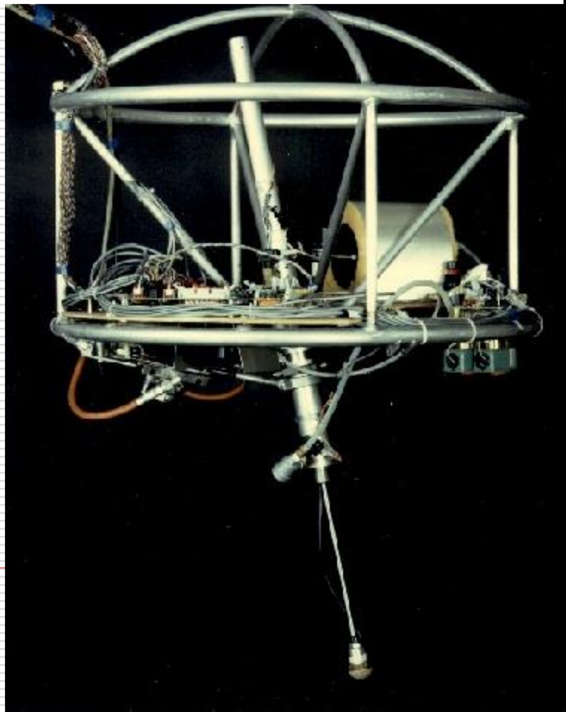
- Actuated robots built according to these principles can walk with a remarkable efficiency
- One of them, the Cornell Ranger, currently holds the distance record for autonomous legged robots.
- Ranger walks non-stop 65.2 km (40.5) mile ultra-Marathon on May 1-2, 2011
- Ranger's energy use was reduced by 43% from July 2010 when Ranger walked 14.3 miles.
- Before that the record was held by Boston Dynamics' BigDog, an all-terrain gas-powered quadruped, which trotted 12.8 miles without refueling.



Examples Of Legged Robot Locomotion: **One Leg**



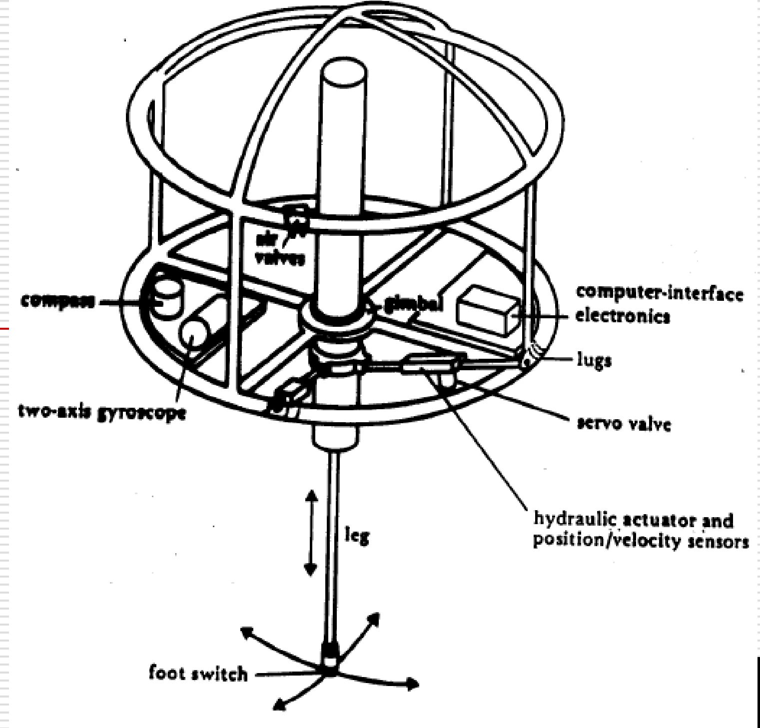
- Single leg minimizes cumulative leg mass.
- No leg coordination is needed.
- Have single points of contact with the ground like a wheel
- By hopping it can cross a gap that is larger than its stride
- The major challenge in creating a single-legged robot is balance.
- Static walking is not only impossible, but static stability when stationary is also impossible.

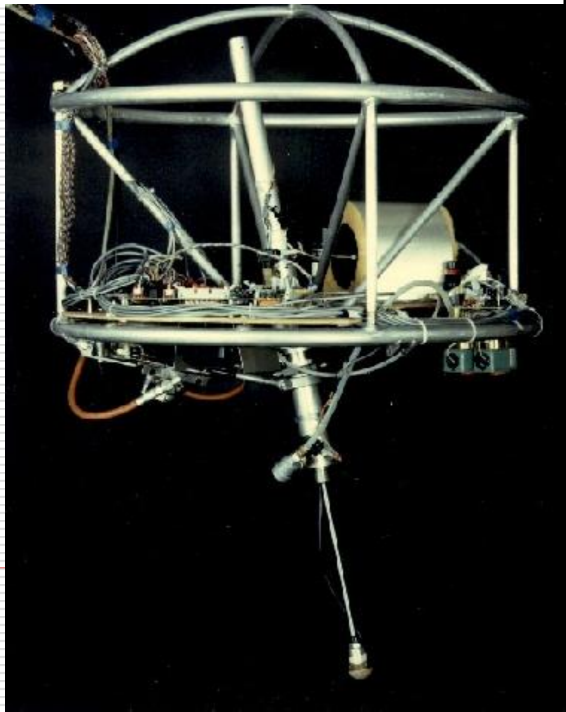


Raibert 3D One-Leg Hopper (1983-1984)

Examples Of Legged Robot Locomotion: **One Leg**

- 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.



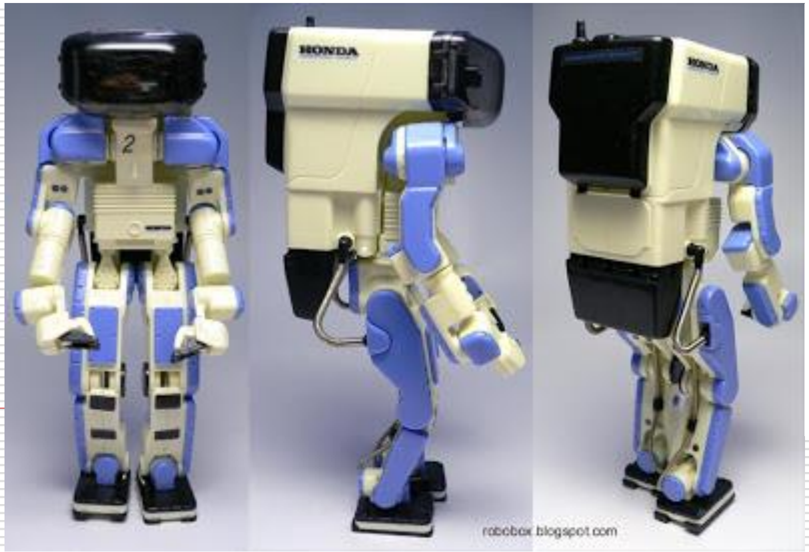


Raibert 3D One-Leg Hopper (1983-1984)

- The Honda humanoid project has a significant history, but, again, it has tackled the very important engineering challenge of actuation.
- Model P2, which is an immediate predecessor to the most recent Asimo (advanced step in innovative mobility)
- Note that the latest Honda Asimo model is still much larger than the SDR-4X at 120 cm tall and 52 kg.
- Perhaps the first robot to demonstrate biomimetic bipedal stair climbing and descending.
- Designed not for human aids throughout society

Asimo (2000)

P2 (1996)



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

- 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-2R is designed to emulate human motion, and it is even designed to dance like a human.

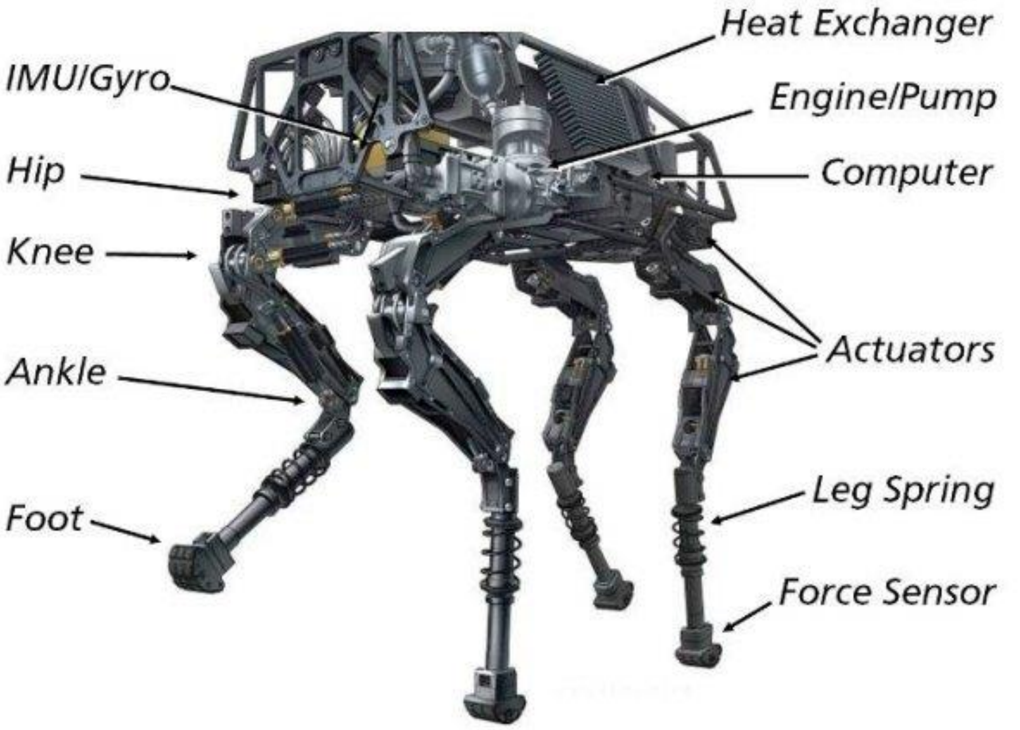
WABIAN-2R (2006)

- Bipedal robots can only be statically stable within some limits, and so robots such as P2 and WABIAN-2R generally must perform continuous balance-correcting servoing even when standing still.

- BigDog is a rough-terrain robot that walks, runs, climbs, and carries heavy loads.
- It is powered by an engine that drives a hydraulic actuation system.
- Its legs are articulated like an animal’s, with compliant elements to absorb shock and recycle energy between two steps.
- LittleDog is a small-size robot designed for research on learning locomotion.
- Each leg has a large range of motion and is powered by three electric motors.

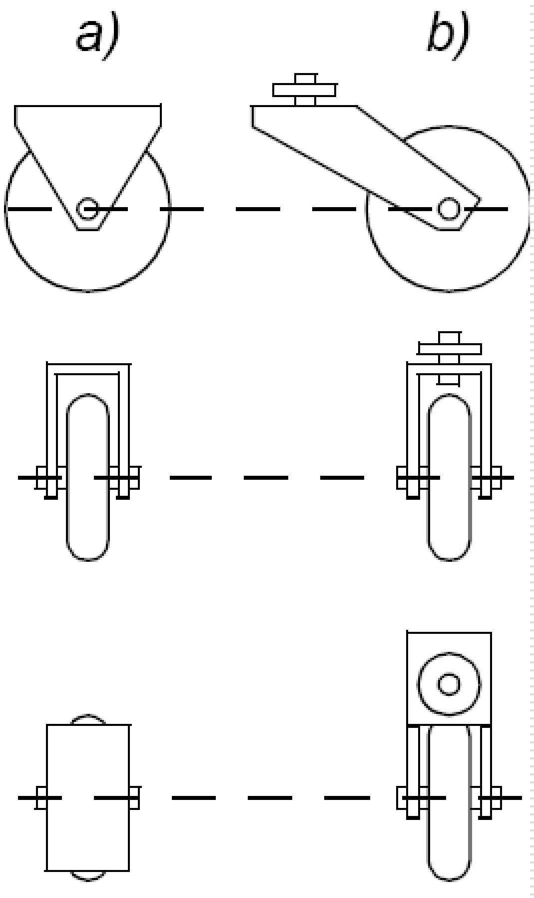
LittleDog (2006)

BigDog (2005)

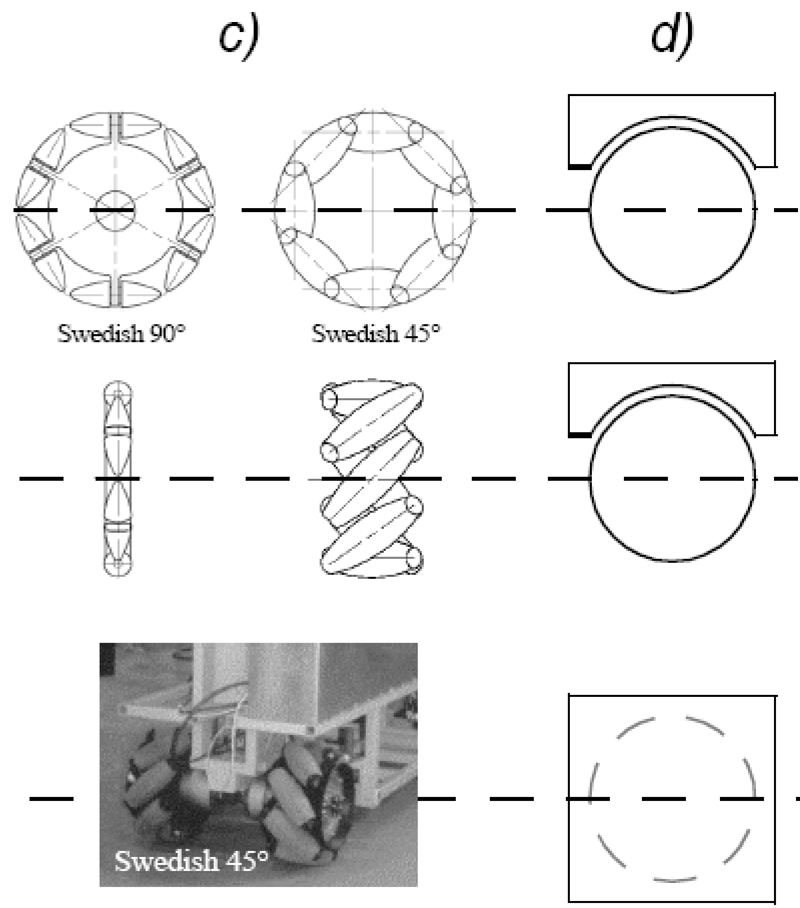


Wheeled Mobile Robots

- There are four major wheel classes
- 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
- Castor wheel rotates around an offset axis, causing a force to be imparted to the robot chassis during steering

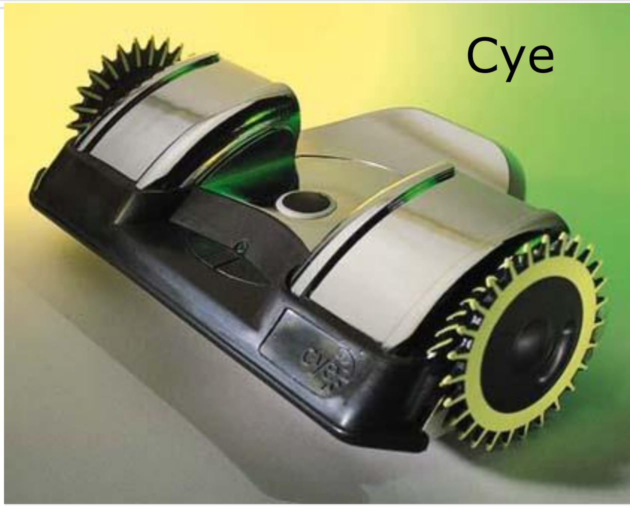


- c) Swedish wheel: Three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers and around the contact point.
- It can kinematically move with very little friction along many possible trajectories, not just forward and backward
- d) Ball or spherical wheel: Suspension technically not solved
- The spherical wheel is a truly omnidirectional wheel.



Stability

- Surprisingly, the minimum number of wheels required for static stability is **two**.
- A two-wheel differential-drive (*separate motor for each wheel*) robot can achieve static stability if the **center of mass is below the wheel axle**.
- This solution requires wheel diameters that are impractically large.
- Dynamics can also cause a third point of contact, for instance, with sufficiently high motor torques from standstill.
- Conventionally, static stability requires a **minimum of three wheels**
- Stability can be further improved by adding more wheels
- As the number of contact points exceeds three, hyperstatic nature of the geometry will require some form of flexible suspension on uneven terrain.



Cye

- The **ground clearance** of robots with **Swedish and spherical wheels** is somewhat limited due to the mechanical constraints of constructing omnidirectional wheels.
- **Four-castor wheel configuration** in which each castor wheel is actively steered and actively translated.
- In this configuration, the robot is <u>truly omnidirectional</u> because, even if the castor wheels are facing a direction perpendicular to the desired direction of travel, the robot can still move in the desired direction by steering these wheels.

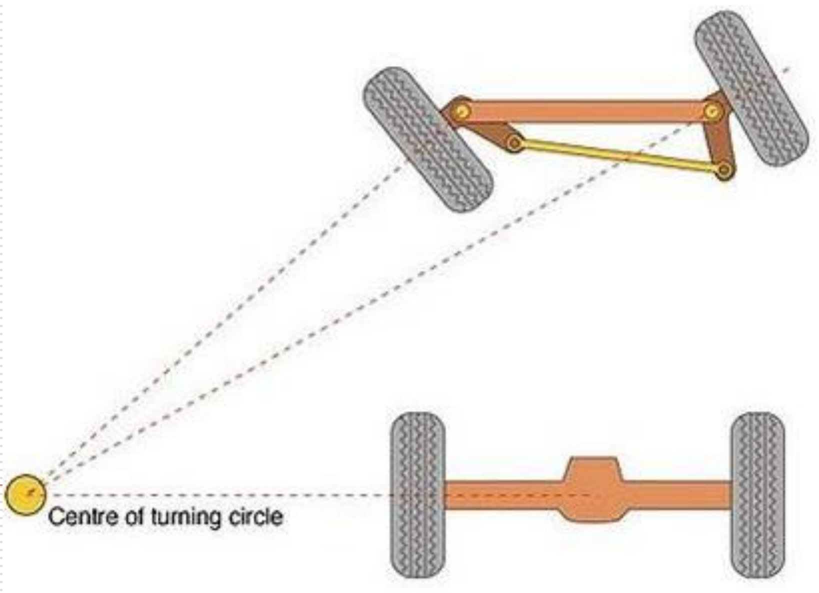
Maneuverability

- It is defined as the quality of being **maneuverable**. **Manuever** is a controlled change in movement or direction of a moving vehicle or vessel.
- Some robots are omnidirectional, meaning that they can move at any time in any direction along the ground plane regardless of the orientation of the robot around its vertical axis.
- This level of maneuverability requires wheels that can move in more than just one direction, and so omnidirectional robots usually employ **Swedish** or **spherical wheels** that are powered.
- A good example is Uranus, a robot that uses four Swedish wheels to rotate and translate independently and without constraints.

Wheel Geometry

- Three fundamental characteristics of a robot are governed by these choices: maneuverability, controllability, and stability.
- There is no single wheel configuration that maximizes these qualities for the variety of environments faced by different mobile robots.

Ackermann Steering



- Few robots use the Ackerman wheel configuration of the automobile,
- because of its poor maneuverability, with the exception of mobile robots designed for the road system

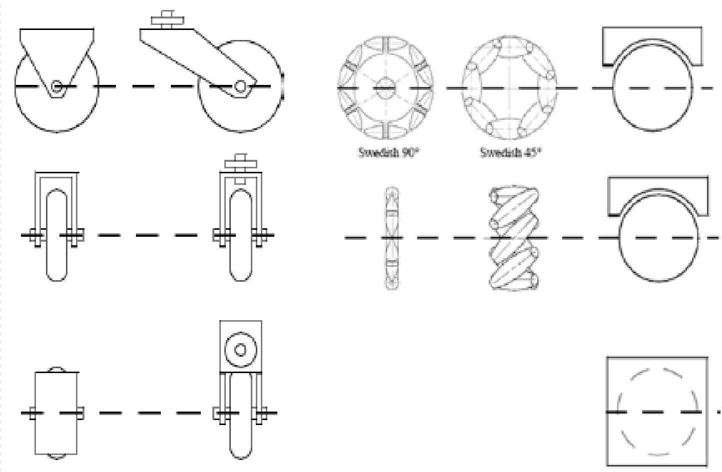
Ackermann Steering

- Mobile Robots Designed For The Road System.
- The Tartan Racing self-driving vehicle developed at CMU, which won the 2007 DARPA Urban Challenge.

Motion Control: Kinematics And Motion Control

- principles of kinematics are applied to the whole robot contributed withwheels, legs, and flight.

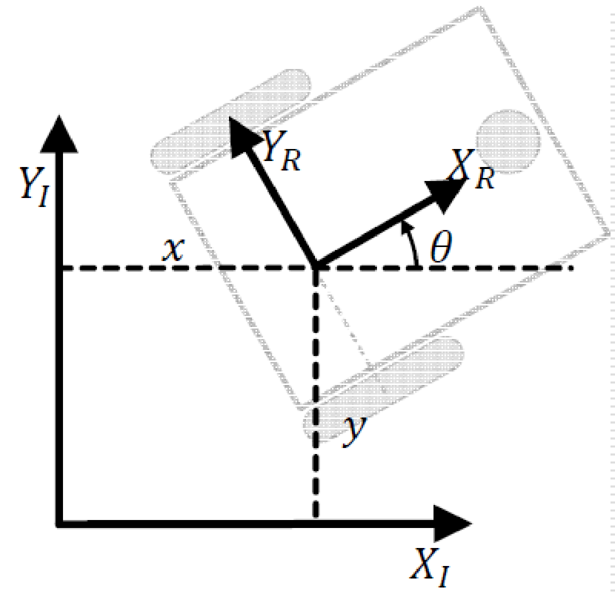
- Motion control



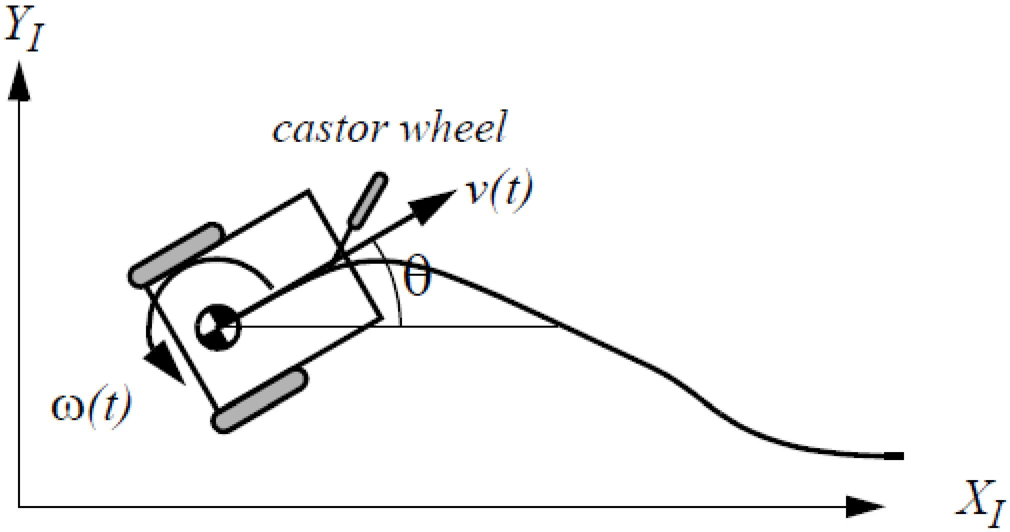
$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = f(\dot{\varphi}_1 \cdots \dot{\varphi}_n, \theta, geometry)$$

$$\begin{bmatrix} \dot{\varphi}_1 \\ \vdots \\ \dot{\varphi}_n \end{bmatrix} = f(\dot{x}, \dot{y}, \dot{\theta})$$

?



P: point between two wheels
r: wheel diameter
l: wheel distance from P
$\dot{\varphi}_1$: spinning speed of first wheel
$\dot{\varphi}_2$: spinning speed of second wheel



$$\dot{\xi}_I = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = f(l, r, \theta, \dot{\varphi}_1, \dot{\varphi}_2)$$

robot's overall speed in the global reference frame

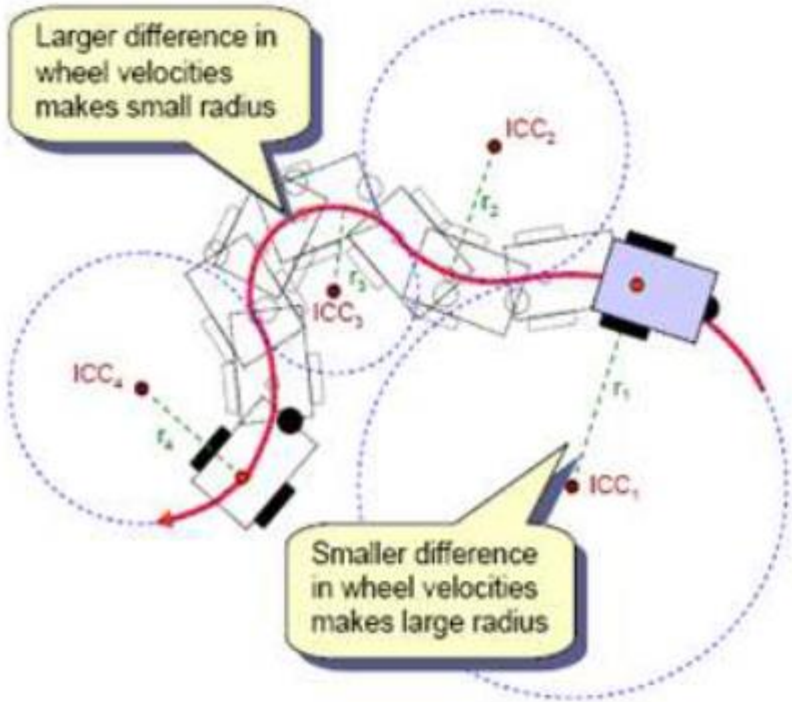
- robot's motion in the global reference frame computed from motion in its local reference frame

$$\dot{\xi}_I = R(\theta)^{-1}\dot{\xi}_R$$

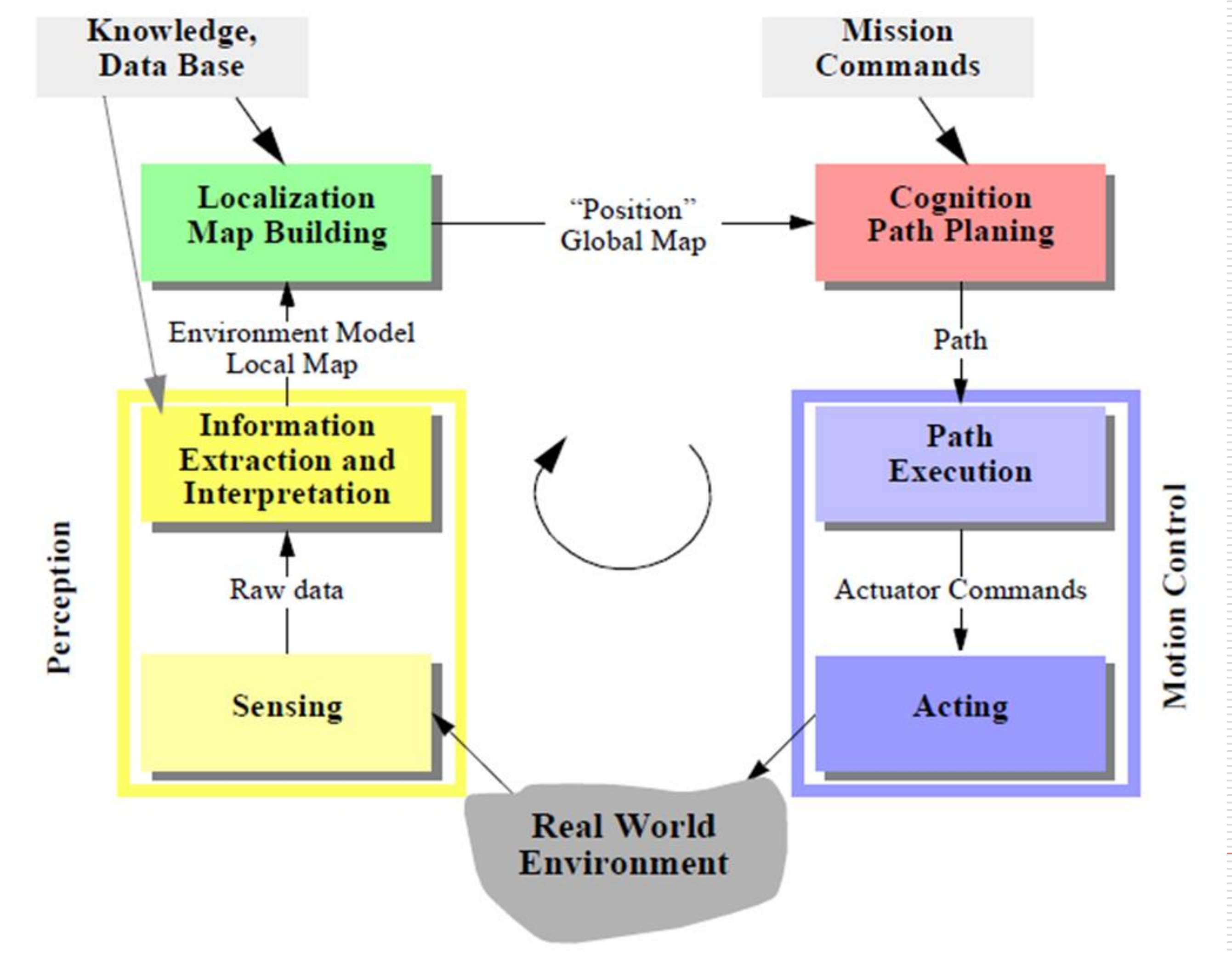
- first compute the contribution of each of the two wheels in the local reference frame $\dot{\xi}_R$

Instantaneous Center of Rotation (ICR)

- The ICR has a zero motion line drawn through the horizontal axis perpendicular to the wheel plane
- The wheel moves along a radius R with center on the zero motion line, the center of the circle is the ICR
- ICR is the point around which each wheel of the robot makes a circular course
- The ICR changes over time as a function of the individual wheel velocities



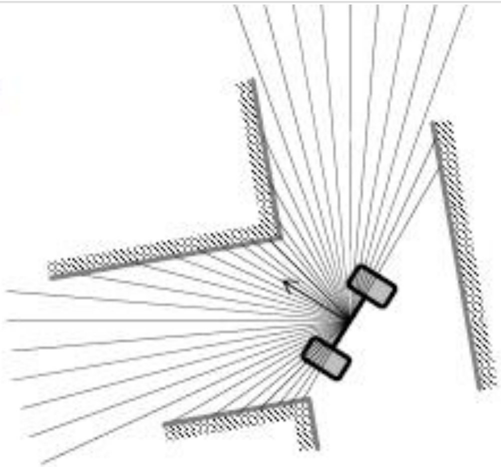
The see-think-act Cycle



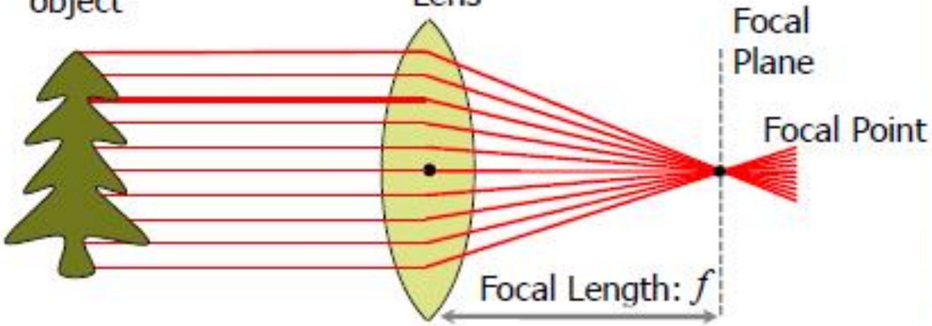
Perception

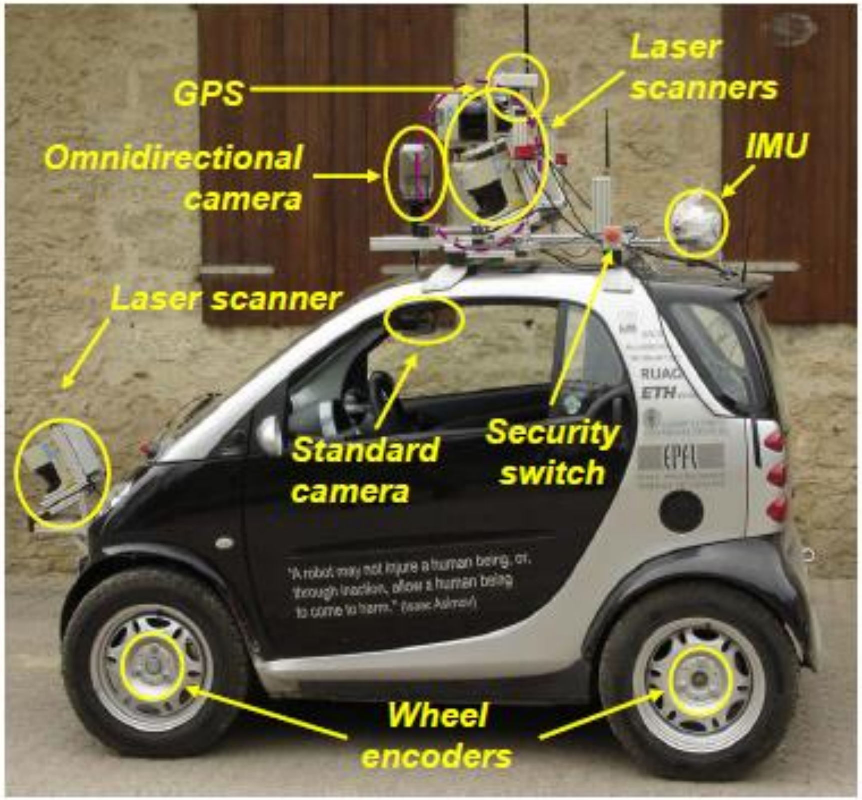
- Sensors available to the mobile roboticist
- The most promising sensor for the future of mobile robotics is vision

- Laser scanner
  - time of flight



- Camers





Perception: Information Extraction

- Perception is also the interpretation of sensed data in meaningful ways.

- Filtering / Edge Detection

- Keypoint Features
  - features that are reasonably invariant to rotation, scaling, viewpoint, illumination
  - FAST, SURF, SIFT, BRISK, ...

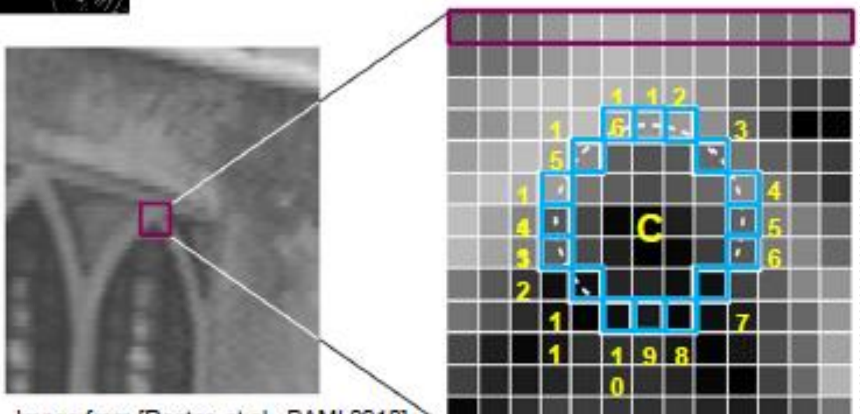
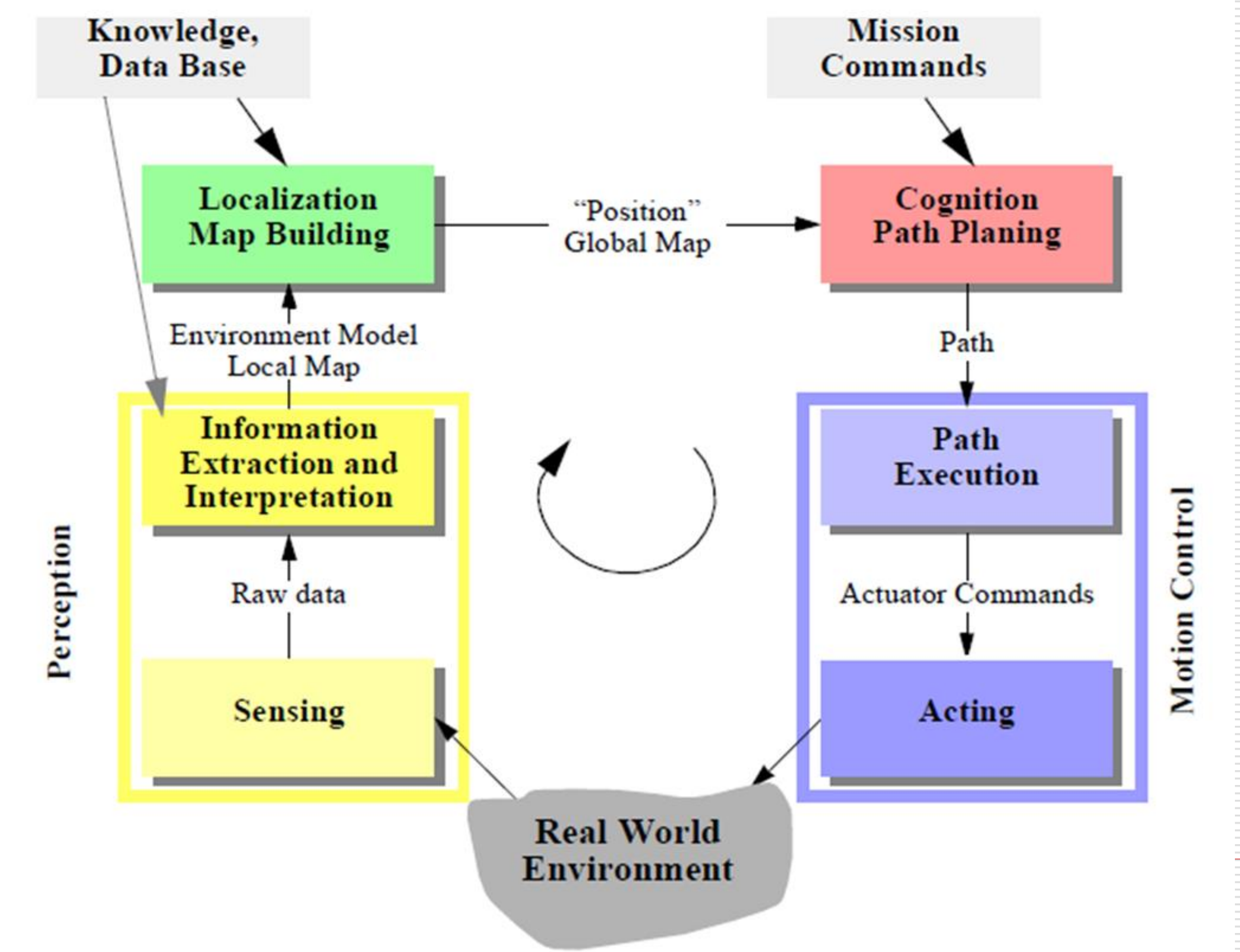


Image from [Rosten et al., PAMI 2010]

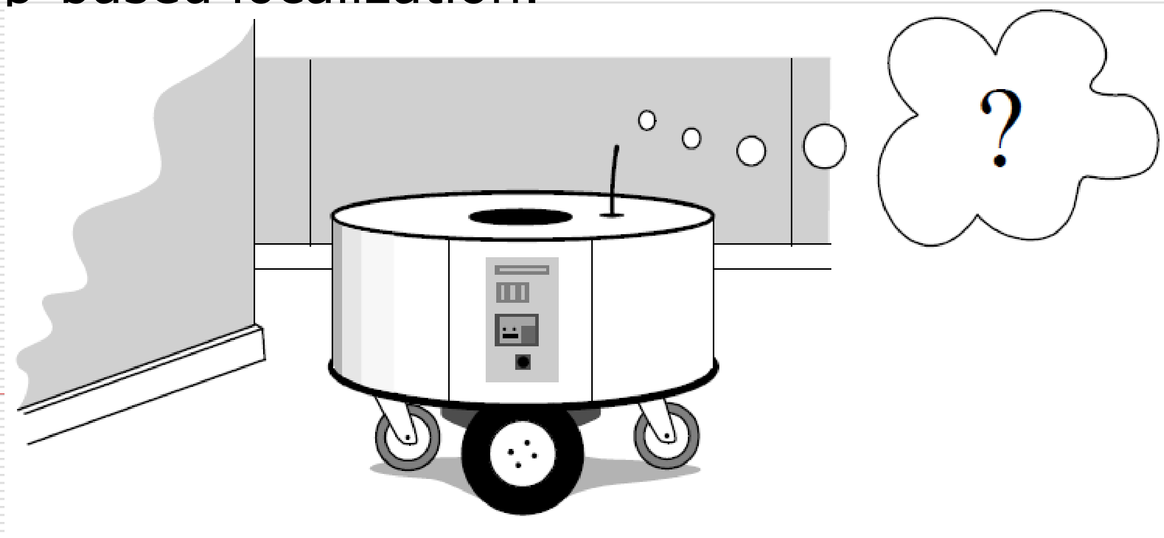
- Keypoint matching
  - BRISK example

The see-think-act Cycle

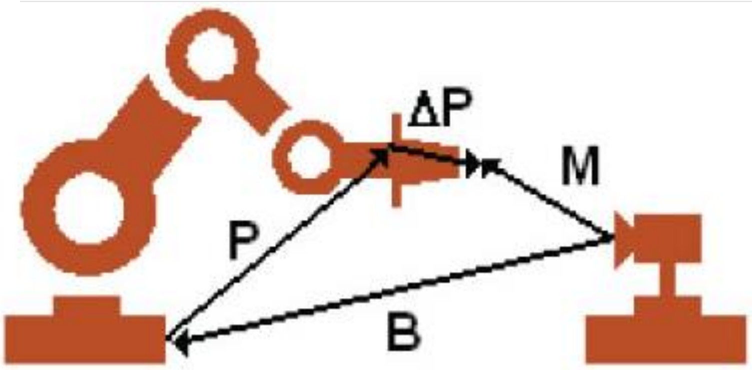


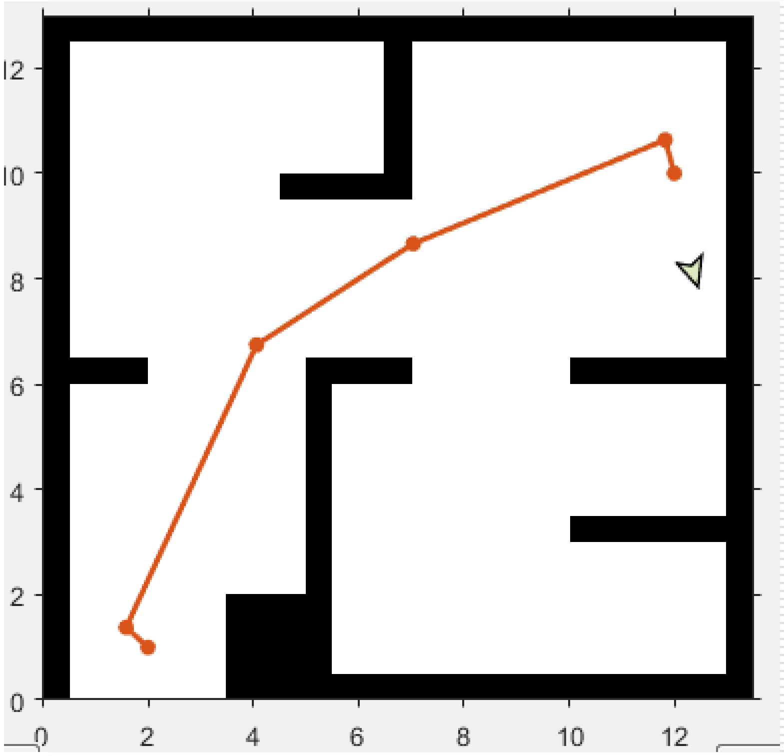
Localization

- The successful localization methodologies of recent years.
- How sensor and effector uncertainty is responsible for the difficulties of localization.
- two extreme approaches to dealing with the challenge of robot localization:
  - avoiding localization altogether, and
  - performing explicit map-based localization.
- case studies of successful localization systems



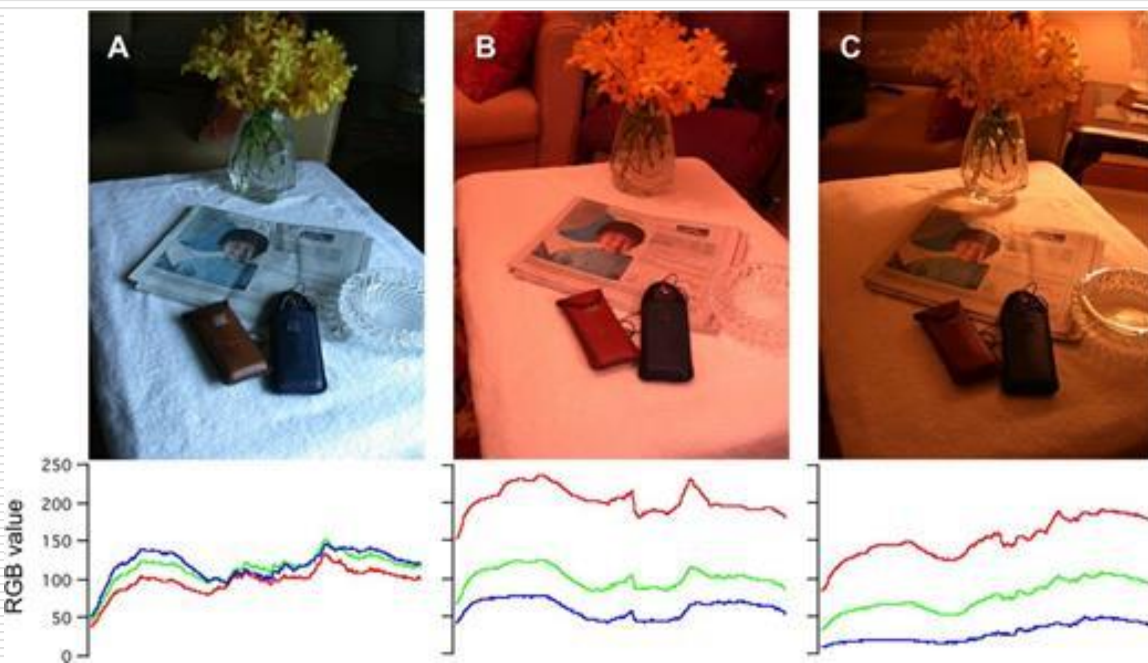
- **Absolute position** of a robot is as important as but its **relative position**
- To reach a particular location, then **localization** may not be enough.
- The robot may need to acquire or build an environmental model, **a map**, that aids it in planning a path to the goal.
- Localization means
  - determining an **absolute pose** in space;
  - building a **map**, to identify robot's position relative to that map

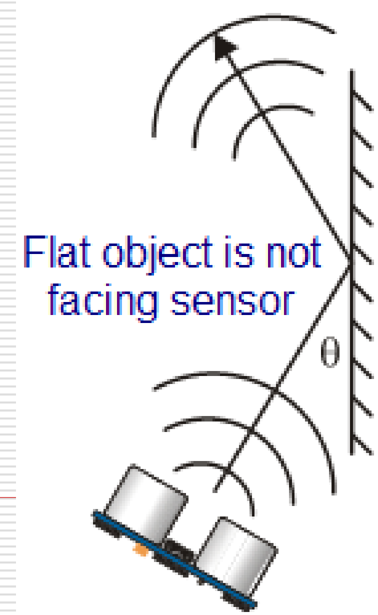




The Challenge of Localization: Noise and Aliasing

- Sensor noise induces a limitation
  - CCD produces different hue values under different illumination conditions such as sun and cloud positions
  - Sonar transducer emits sound toward a relatively smooth and angled surface, there will be no echo

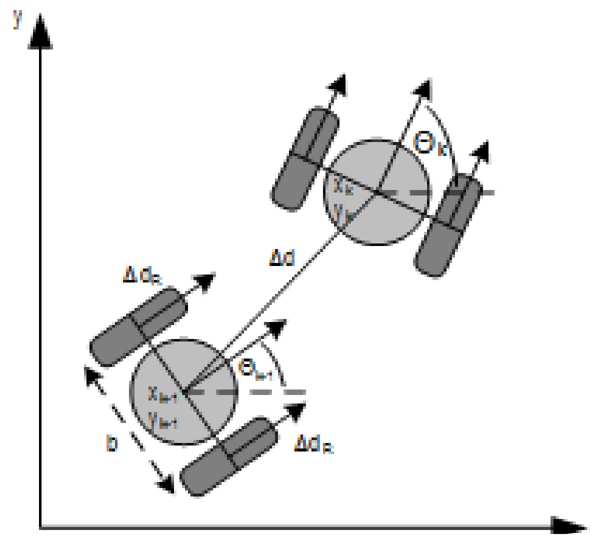




Sensor aliasing

- In robots, the nonuniqueness of sensor readings, or sensor aliasing, is the norm and not the exception
- The problem posed to navigation because of sensor aliasing is that, even with noise-free sensors, the amount of information is generally insufficient to identify the robot’s position from a single-percept reading.
- Robot’s localization is usually based on a series of readings
- Sufficient information is recovered by the robot over time

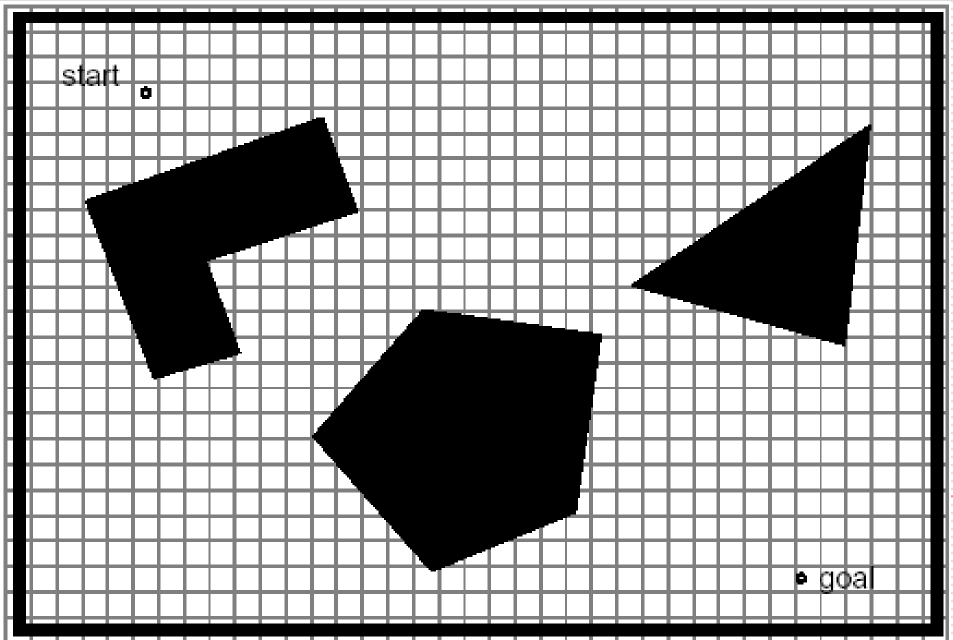
Effector noise

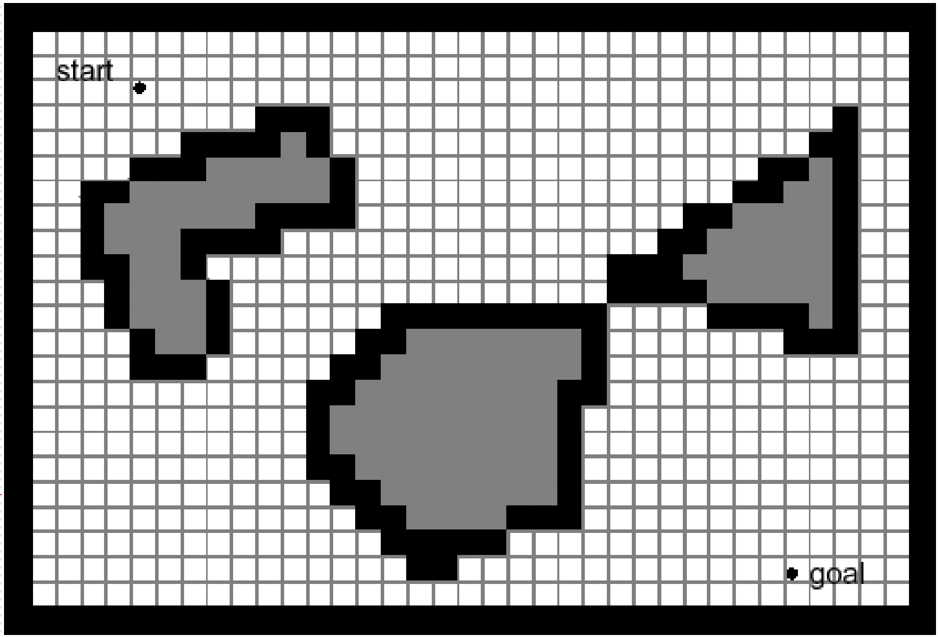


- In odometry (wheel sensors only) and dead reckoning (also heading sensors) the position update is based on proprioceptive sensors.
- The movement of the robot, sensed with wheel encoders or heading sensors or both, is integrated to compute position.
- Because the sensor measurement errors are integrated, the position error accumulates over time.
- Thus, the position has to be updated from time to time by other localization mechanisms.
- Otherwise the robot is not able to maintain a meaningful position estimate in the long run.

Fixed cell decomposition

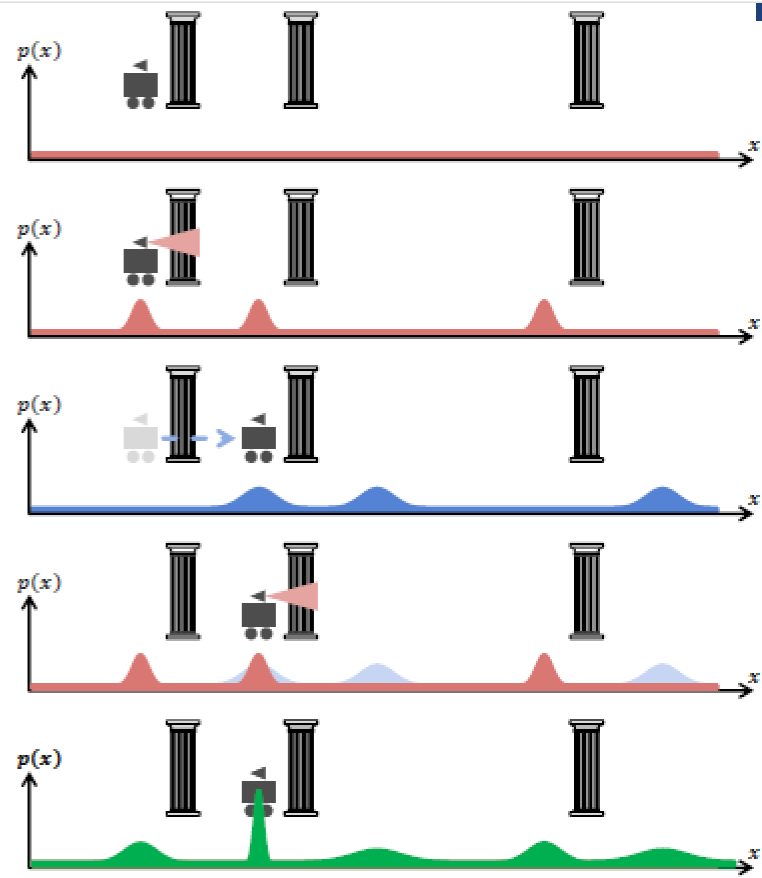
- The world is tessellated, transforming the continuous real environment into a discrete approximation for the map.
- Figure on the right depicts what happens to obstacle-filled and free areas during this transformation.
- The key **disadvantage** of this approach is that possible for **narrow passageways to be lost** during such a transformation.



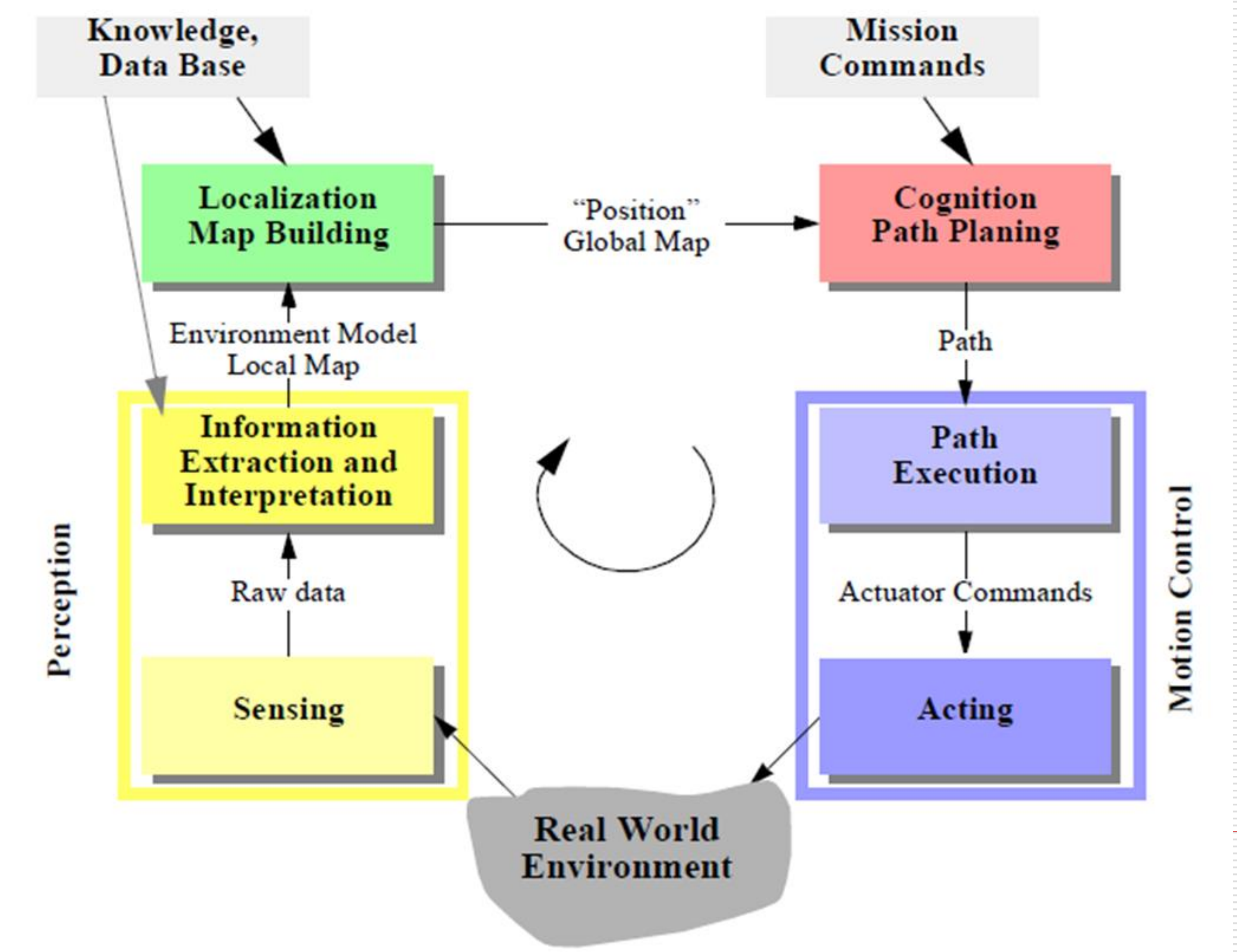


Localization: Where Am I?

- SEE: The robot queries its sensors → finds itself next to a pillar
- ACT: Robot moves one meter forward motion
  - estimated by wheel encoders
  - accumulation of uncertainty
- SEE: The robot queries its sensors again → finds itself next to a pillar
- Belief update (information fusion)

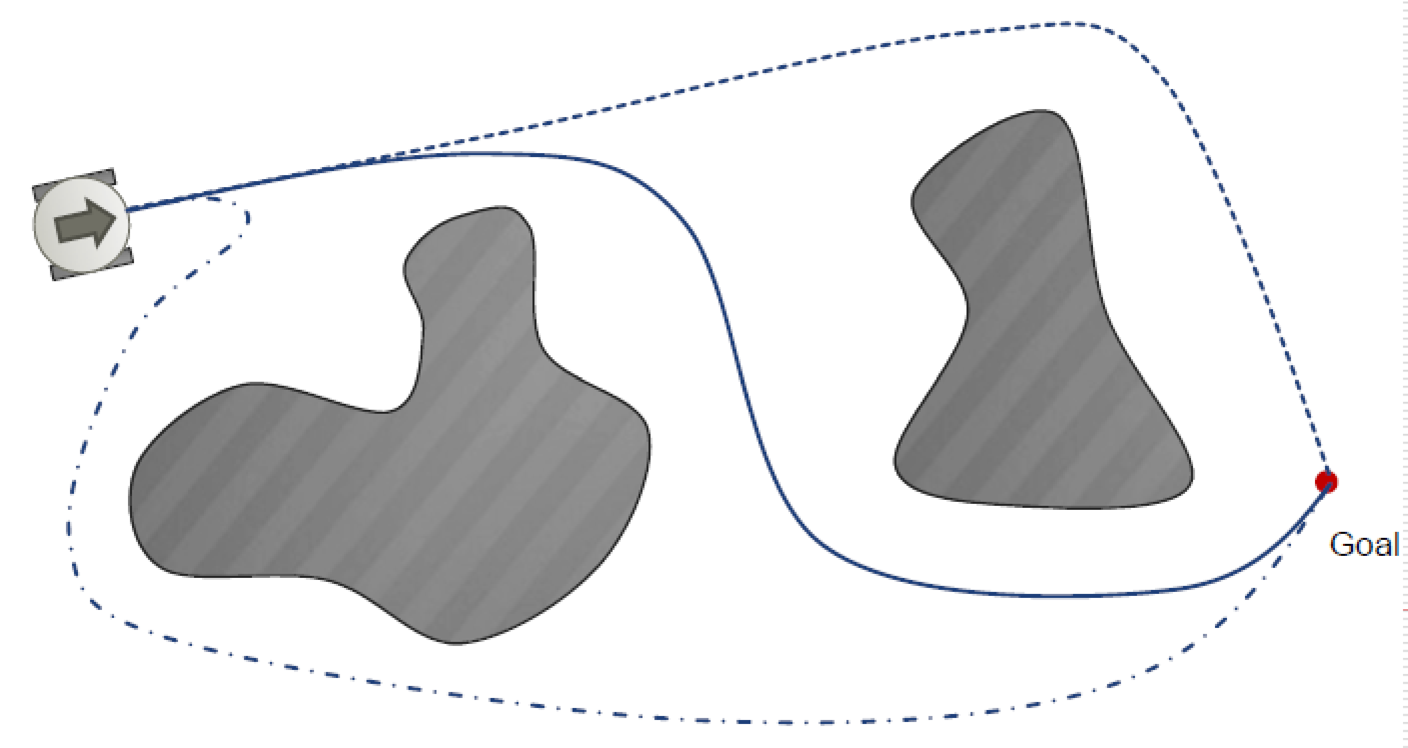


The see-think-act Cycle

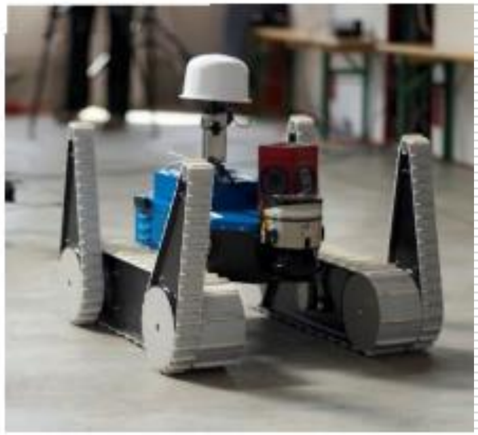


Cognition:
Where am I going? How do I get there?

- Planning and Navigation surveys the today's various techniques differing primarily in the manner in which they decompose the problem of robot control.
- Navigating robot usually must demonstrate: obstacle avoidance and path planning.



Some Recent Examples



UAV:collision avoidance and path planning

- Real time 3D mapping (on-board)
- Optimal path planning considering localization uncertainties

Rezero: Wheeled locomotion with single point contact

- Up to 17° tilt angle
- Up to 3.5 m/s

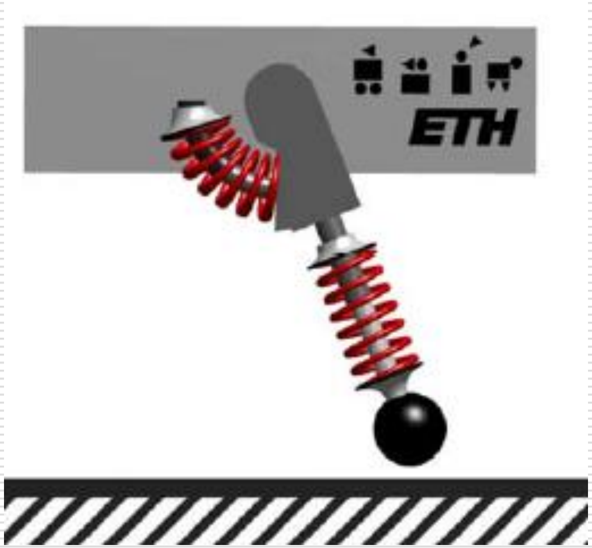
Wheel design adopted from Kumagai & Ochiai,
Tohoku Gakuin Universtity, Japan

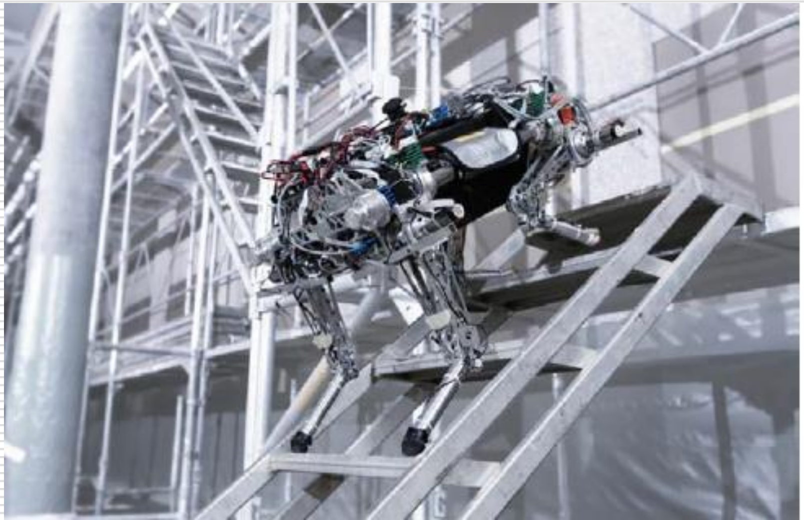
rezero
the ultimate ballbot

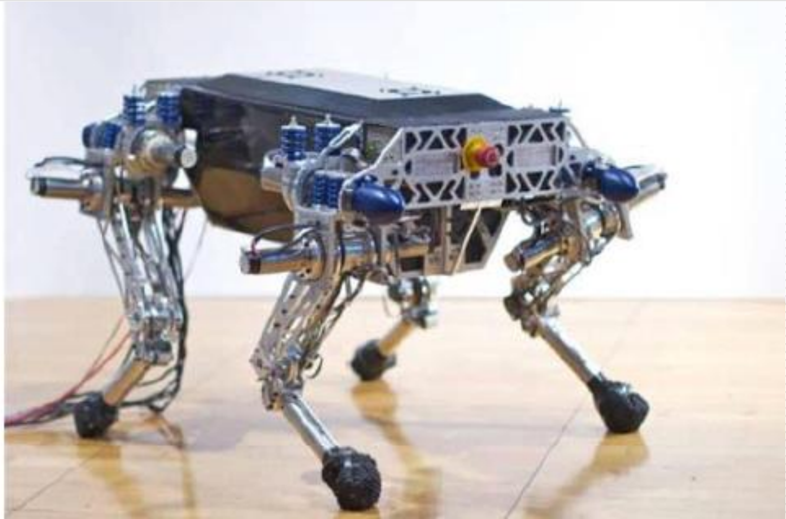
http://www.rezero.ethz.ch/

Efficient Walking and Running: Serial Elastic Actuation

- StarlETH
- agile, efficiency and robust







Humanoid Robot: ASIMO

- Honda’s ASIMO - Advanced Step in Innovative MObility
- Designed to help people in their everyday lives
- One of the most advanced humanoid robots
  - Compact, lightweight
  - Sophisticated walk technology
  - Human-friendly design

Beyond Mobility:
PR2 robot from Willow Garage

Fold towels

Courtesy of Willow Garage

Clean-up

Text Book

- Introduction to Autonomous Mobile Robots, Second Edition
- By Roland Siegwart, Illah Reza Nourbakhsh and Davide Scaramuzza