Week 1

Introduction

(Overview)

What is Perception and Planning?

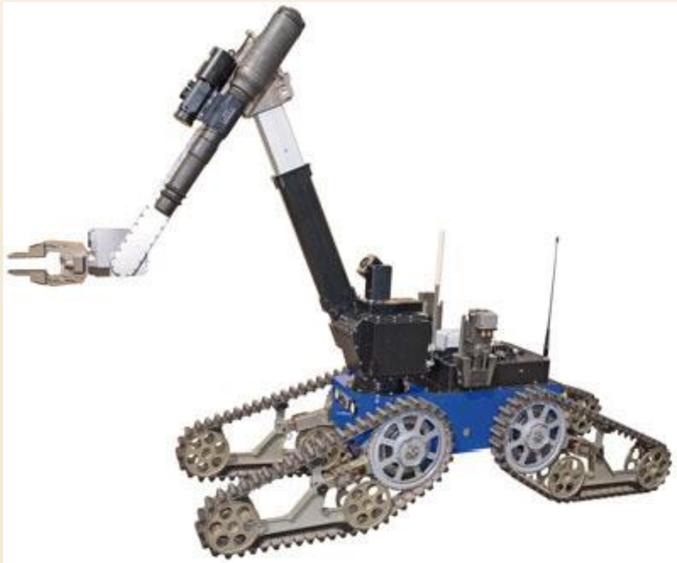
- For robots and intelligent machines to do complex tasks in the complex environment, they require the ability to perform both perception and planning.

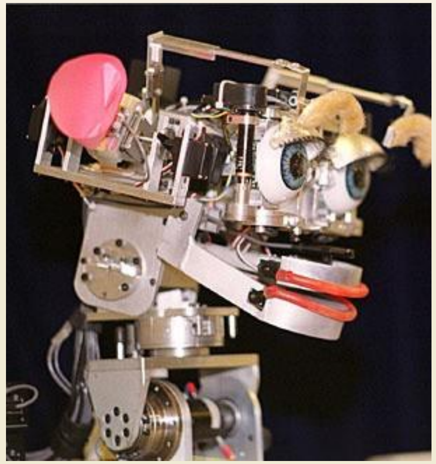
- Perception and planning involves using sensors to sense the environment and sensor data processing to making appropriate decisions.

What is Perception and Planning?

- Some problems:
  - How to take sensor data and arrive at an action?
  - How to work out where the robot is?
  - How to decide where the robot should go next?
  - How to devise and organize robot intelligence?
  - How can a robot learn to improve its behavior?
  - ……..

Robots and Automation





Robotics: General Background

- Autonomous, automaton
  - self-willed (Greek, auto+matos)
- Robot
  - Karel Capek in 1923 play R.U.R. (Rossum's Universal Robots)
    - labor (Czech or Polish, robota)
    - workman (Czech or Polish, robotnik)

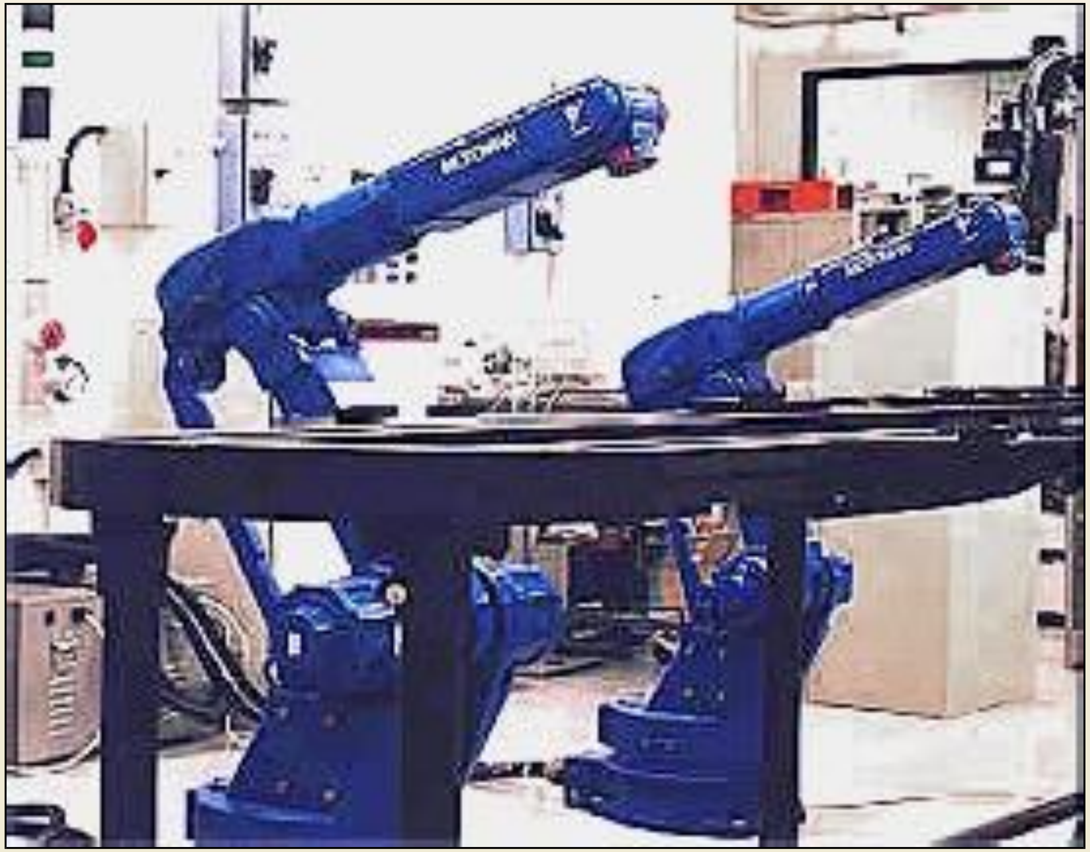
History of Robots

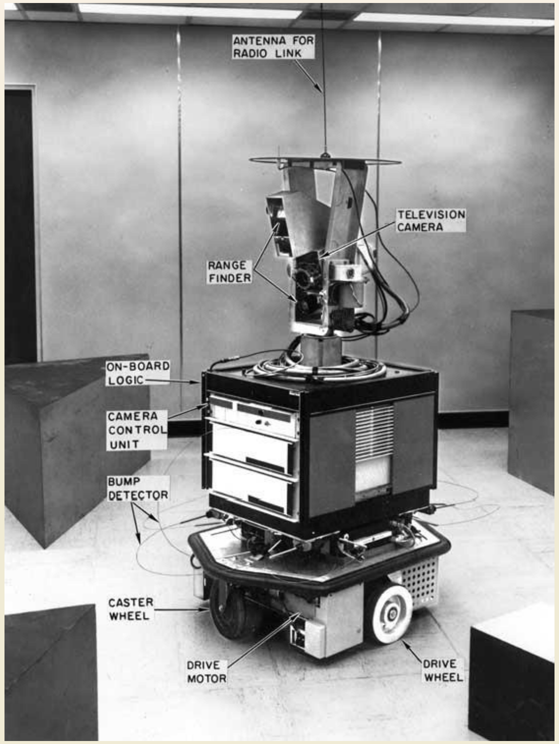
1500's	Leonardo DaVinci designs mechanical armored knight
1700's	Clockwork driven automata for entertainment
1822	Jacquard loom and Charles Babbage's difference engine
1994	Unimate – first industrial robot
1969	Shakey SRI – First robot to perceive and reason!
1980	JPL (NASA) planetary landers & robots
1988	Insect robotics: Reactive subsumption
1995	Internet agents (web robots) are born
1996	NavLab - self-driving vehicles traverses USA
1997	Honda releases the Honda walking robot program
1997	Mars Pathfinder / Sojourner lands on Mars
1998	RoboCup - Soccer robotics becomes big!
1999	Sony AIBO robot dog released
2000	Rotary molecular motor devised
2001	CyberKnife to treat tumors anywhere in the body
2002	Honda ASIMO rings open bell at NY Stock Exchange
2002	Roomba- robotic vacuum cleaner released
2004	NASA MER rovers, Sprint & Opportunity, land on Mars
2005	Self-driving vehicle drives across USA
2012	Robonaut enters International space station
2021	Mars rover Perseverance landed on Mars

Maillardet's Automaton

Unimate

Robotics Yesterday





Traditional Industrial Robots

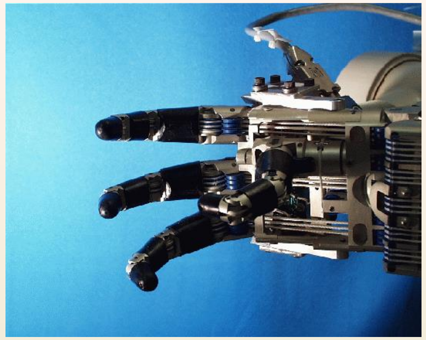
- Traditional industrial robot control uses robot arms and largely pre-computed motions
  - Programming using “teach box”
  - Repetitive tasks
  - High speed
  - Few sensing operations
  - High precision movements
  - Pre-planned trajectories and
  - task policies
  - No interaction with humans

Current Trends in Robotics

Robots are moving away from factory floors to

- Entertainment, toys
- Personal services
- Medical, surgery
- Industrial automation (mining, harvesting, …)
- Hazardous environments (space, underwater)
- Self driving vehicles

Robotics Today



RoboCup, Stockholm, Sweden, 1999

RoboCup, Montreal, Canada, 2018

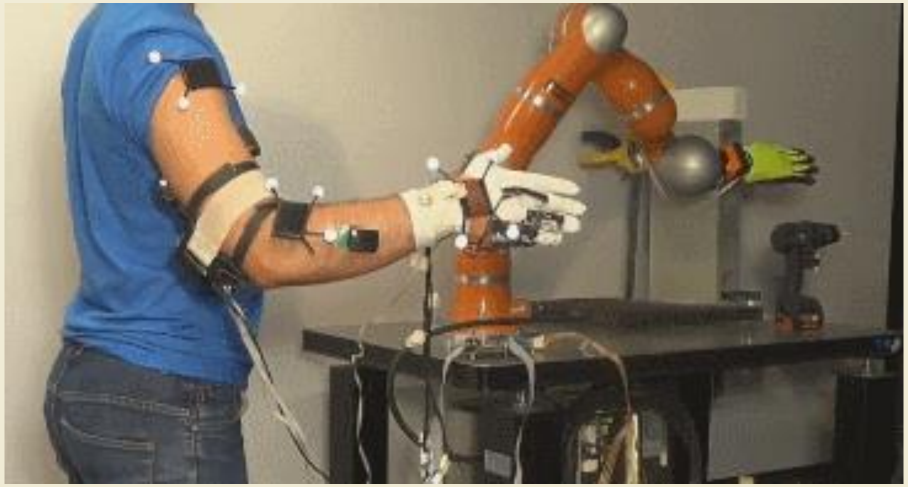
Each team is fully autonomous in all RoboCup leagues. Once the game starts, the only input from any human is from the referee.

RoboCup editions [edit]

Number	Year	Host City	Host Country	Number of teams	Number of countries
1	RoboCup 1997	Nagoya	Japan	38	11
2	RoboCup 1998	Paris	France	63	19
3	RoboCup 1999	Stockholm	Sweden	85	23
4	RoboCup 2000	Melbourne	Australia	110	19
5	RoboCup 2001	Seattle	United States	141	22
6	RoboCup 2002	Fukuoka	Japan	197	29
7	RoboCup 2003	Padua	Italy	238	35
8	RoboCup 2004	Lisbon	Portugal	345	37
9	RoboCup 2005	Osaka	Japan	387	36
10	RoboCup 2006	Bremen	Germany	440	35
11	RoboCup 2007	Atlanta	United States	321	39
12	RoboCup 2008	Suzhou	People's Republic of China	373	35
13	RoboCup 2009	Graz	Austria	407	43
14	RoboCup 2010	Singapore	Singapore	500	40
15	RoboCup 2011	Istanbul	Turkey	451	40
16	RoboCup 2012	Mexico City	Mexico	381	42
17	RoboCup 2013	Eindhoven	Netherlands	410	45
18	RoboCup 2014	João Pessoa	Brazil	358	45
19	RoboCup 2015	Hefei	People's Republic of China[9]	346	43
20	RoboCup 2016	Leipzig	Germany[10]	404	45
21	RoboCup 2017	Nagoya	Japan[11]	500	50
22	RoboCup 2018	Montreal	Canada	360	40
23	RoboCup 2019	Sydney	Australia	335	40
24	RoboCup 2021	Virtual		317	43
25	RoboCup 2022	Bangkok	Thailand		
26	RoboCup 2023	Bordeaux	France		

The formal RoboCup competition was preceded by the (often unacknowledged) first International Micro Robot World Cup Socce

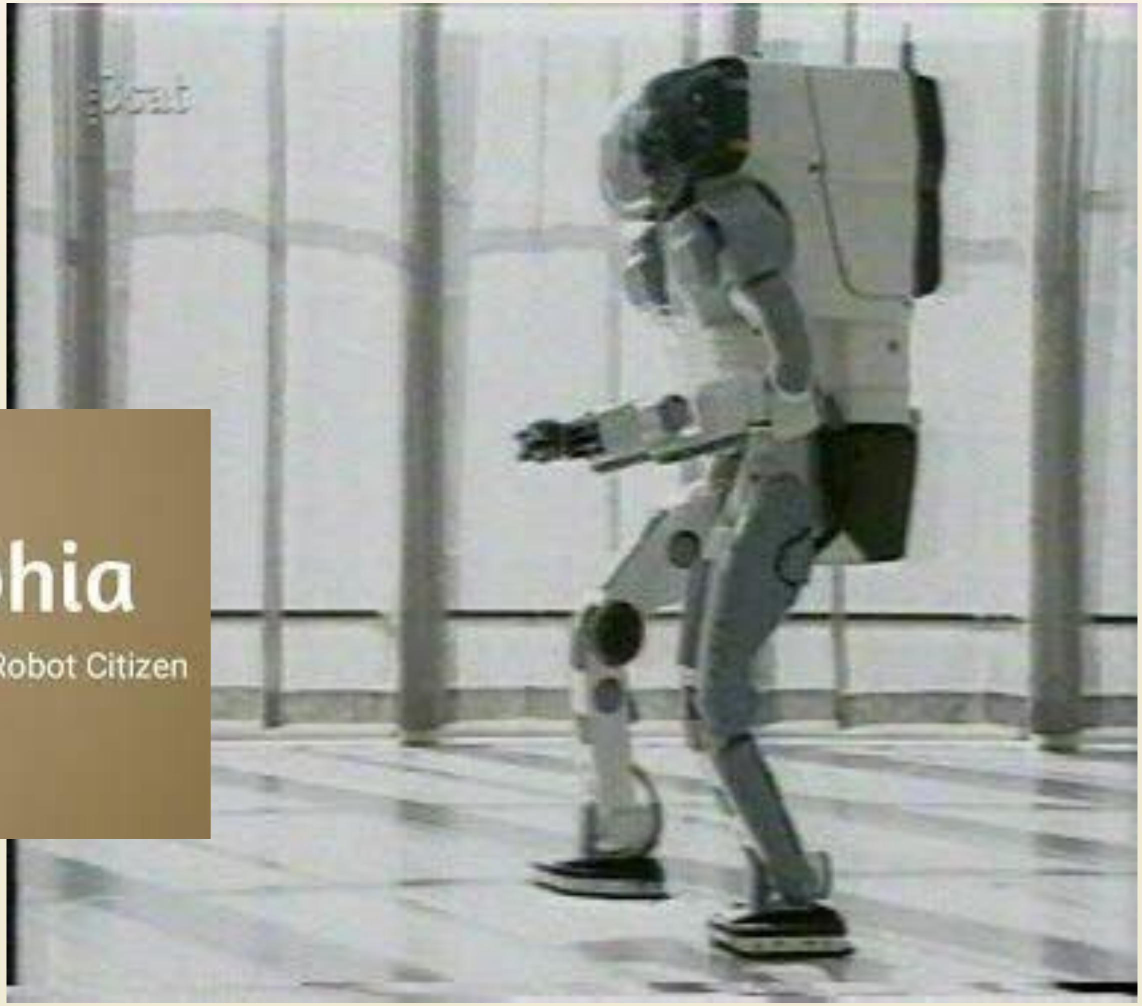
Teleoperated Robots



Still a robot, but not autonomous.

Mobile Manipulation

Humanoids



Honda P2 ‘97

Emotional Robots: Cog & Kismet

[Brooks et al., MIT AI Lab, 1993-today]

Museum Tour-Guide Robots

Rhino, 1997

Minerva, 1998

Self Driving Vehicles

https://www.youtube.com/watch?time_continue=874&v=9PIJKE5KMtU

who？

Tsinghua University's first virtual student:Hua Zhibing

What else can you learn about Hua Zhibing other than her beautiful face and voice?

Abilities:
Hua Zhibing can compose poetry, paint, and compose music, and has some ability to reason and interact emotionally.
Unlike a typical virtual digital human, Hua Zhibing can continuously "learn" the patterns implicit in data, including text, visuals, images, videos, etc. Over time, the new capabilities learned for new scenarios will be organically integrated into its own model, thus becoming smarter and smarter.

Implicit technical :

Faces, songs, biological features, etc. are generated by AI models, the body movements are trained by scientists.
For example, the score is applied to the end-to-end model Chord based Rhythm and Melody CrossGeneration Model + Multi-Instrument Co-Arrangement Model [1].
The poetry and painting are applied to the pre-training model with Inverse Prompt and CogView respectively [2] [3].

You can understand Hua Zhibing as: a huge AI framework containing more than 1000 models.

Problems:

Hua Zhibing currently only has a virtual form, not a physical one. So, how does the Hua Zhibing demo video do it?
The answer is AI face replacement.

Is there meaning?
Is the technology used in the Hua Zhibing video just AI face swapping?
Obviously not: Hua Zhibing uses a virtual face created from nothing that can perfectly match the expressions of real people, which is difficult to reach with ordinary technology, and its essence Xiao ice framework X Studio, X Avatar technology figurative display, involving CV, NLP, AI created emotional interaction framework, retrieval model, generative model, sympathetic model and many other important AI issues .

Significance:

First, Hua Zhibing acts as a vehicle to verify the effectiveness of large-scale pre-trained models.
Second, the virtual image technology itself, can present the high threshold AI problems in another more understandable presentation form.

【1】XiaoIce Band: A Melody and Arrangement Generation Framework for Pop Music.
【2】CogView: Mastering Text-to-Image Generation via Transformers.
【3】Controllable Generation from Pre-trained Language Models via Inverse Prompting.

Asimov’s Three Laws of Robotics

1. A robot may not injure a human being, or, through inaction, allow a human being to come to harm.

2. A robot must obey the orders given it by human beings except when such orders would conflict with the first law.

3. A robot must protect its own existence as long as such protection does not conflict with the first or second law.

[Runaround, 1942]

Trends in Robotics Research

Classical Robotics (mid-70's)
exact models
no sensing necessary

Reactive Paradigm (mid-80's)
no models
relies heavily on good sensing

Hybrids (since 90's)
model-based at higher levels
reactive at lower levels

Probabilistic Robotics (since mid-90's)
seamless integration of models and sensing
inaccurate models, inaccurate sensors

Robot Control

- A robot can be defined as a computer controlled machine with some degrees of freedom
  - that is, the ability to move in its environment
- Robots come in many shapes and sizes. E.g. manipulator, mobile robot, submersible, UAV, and operate in either structured or unstructured environments.

Robot Control

- A structured environment is an unnatural environment with added features intended to facilitate the robot's operation. E.g. lines to follow a path, barcodes to identify an object, etc.

- An unstructured environment is a natural or human environment that has not been modified to facilitate the robot. (Much harder to do.)

Robot Control

- A robot typically has
  - sensors to sense its environment, e.g. to make sure it does not hit any obstacles
  - Goals, e.g. knowing where to go next

- The robot usually has a 3-phase sequence of operations:
  - sense (perception),
  - process (interpretation and planning),
  - action (movement of some kind)

Robot Control

- Planning is needed to determine how to accomplish goals
- Some robots have pre-programmed steps to carry out the given goals, so planning is not needed
- Path planning involves determining how to move within the environment based on what is known and using the available degrees of freedom
- This may be the motion of an arm to pick something up, or it may be a series of movements to physically move from one location to another

Robot Control

- The control of autonomous robots involves a number of subtasks
  - Understanding and modeling of the mechanism
    - Kinematics, Dynamics, and Odometry
  - Reliable control of the actuators
    - Closed-loop control
  - Generation of task-specific motions
    - Path planning
  - Integration of sensors
    - Selection or fusion of various types of sensors
  - Coping with noise and uncertainty
    - Filtering out sensor noise and actuator uncertainty
  - Creation of flexible control policies
    - Control has to deal with new situations

Problems

- Traditional programming techniques for industrial robots lack key capabilities needed by robots in unstructured environments
  - Only limited to on-line sensing
  - No incorporation of uncertainty
  - No interaction with humans
  - Reliance on perfect task information
  - Complete re-programming required for new tasks

Structured Environment

Requirements for Robots in Unstructured Environments

- Autonomy
  - Robots have to be capable of achieving task objectives without human input
  - Robots have to be able to make and execute their own decisions based on sensor information
- Improvisation
  - The robot needs to know when a goal has been achieved, and more importantly, when to give up on one goal and find another goal to achieve
- Adaptation
  - Robots have to be able to adjust to changes in the environment and possibly learn from experience

Robots for Unstructured Environments

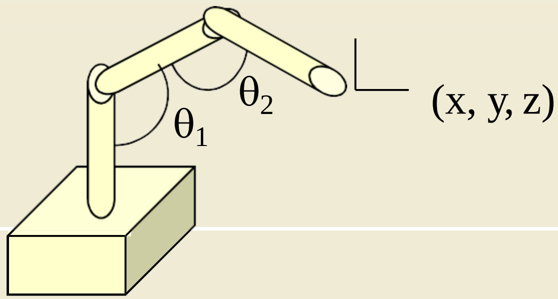
- Service Robots
  - Security guard
  - Delivery
  - Cleaning
  - Mowing
- Assistance Robots
  - Mobility
  - Services for elderly and people with disabilities

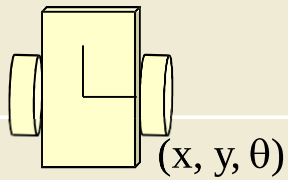
Autonomous Robot Controllers

- To control robots to perform tasks autonomously a number of tasks have to be addressed:
  - Modeling of robot mechanisms
    - Kinematics, Dynamics
  - Robot sensor selection
    - Vision, sonar, active or passive
  - Low-level control of actuators
    - Wheels or legs - closed-loop reactive control
  - Control architectures
    - Traditional planning architectures
    - Behavior-based control architectures
    - Hybrid architectures

Modeling the Robot Mechanism

- Forward kinematics describes how the robot arm joint angle configurations translate to locations in the world





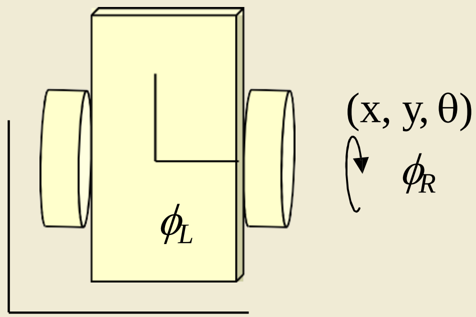
- Inverse kinematics computes the joint angle configuration necessary to reach a particular point in space.
- Jacobian matrices can calculate how the speed and configuration of the actuators translate into velocity of the robot

Mobile Robot Odometry

- In mobile robots the same configuration in terms of joint angles does not identify a unique location
  - To keep track of the robot it is necessary to incrementally update the location. This process is called odometry (or dead reckoning).

$$\begin{pmatrix} x \\ y \\ \theta \end{pmatrix}^{t+\Delta t} = \begin{pmatrix} x \\ y \\ \theta \end{pmatrix}^{t} + \begin{pmatrix} v_x \\ v_y \\ \varpi \end{pmatrix} \Delta t$$

- Example: Differential drive robot:



Robot Navigation

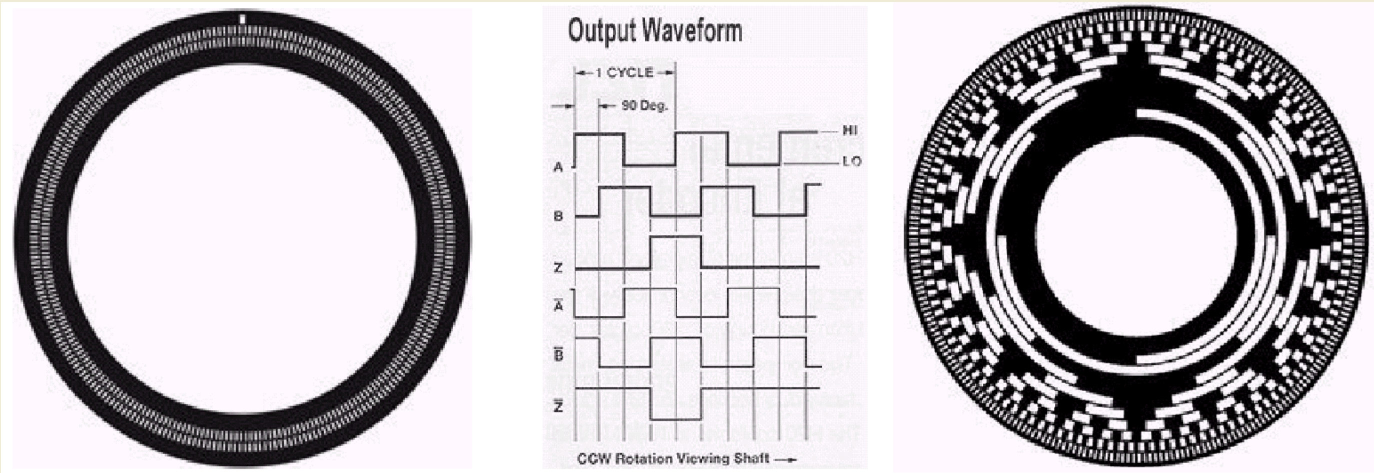
- Path planning involves computing a trajectory for the robot such that it reaches the desired goal without colliding with obstacles
  - Optimal paths can be hard to compute. Particularly for robots that can not move in arbitrary directions (i.e. non-holonomic robots)
  - Shortest distance paths can be dangerous since they can graze obstacles
  - Paths for robot arms have to take into account the entire robot (not just the end effector)

Sensor-Driven Robot Control

- To accurately achieve a task in an unstructured environment, a robot has to be able to react dynamically to changes to its surrounding
  - Robots need sensors to perceive the environment
  - Most robots use a set of different sensors
    - Different sensors serve different purposes
  - Information from sensors has to be integrated into the control of the robot somehow

Robot Sensors

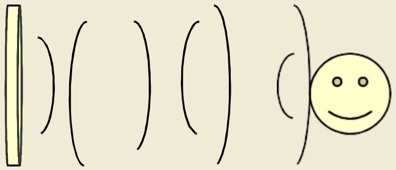
- Internal sensors to measure the robot configuration
  - Encoders measure the rotation angle of a joint



  - Limit switches detect when the joint has reached the limit

Robot Sensors

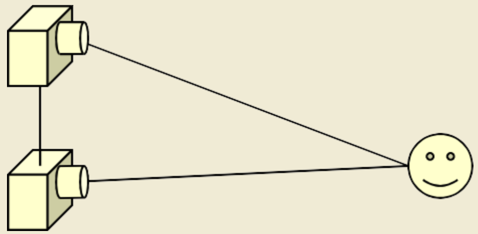
- Proximity sensors are used to measure the distance or the location of objects in the environment. This can then be used to help determine the location of the robot.
  - Infrared sensors determine the distance to an object by measuring the amount of infrared light the object reflects back to the robot
  - Ultrasonic sensors (sonars) measure the time that an ultrasonic signal takes until it returns to the robot



  - Laser range finders determine distance by measuring either the time it takes for a laser beam to be reflected back to the robot or by measuring where the laser hits the object

Robot Sensors

- Computer Vision provides robots with the capability to passively observe the environment
  - Stereo vision systems provide complete 3D location information using triangulation



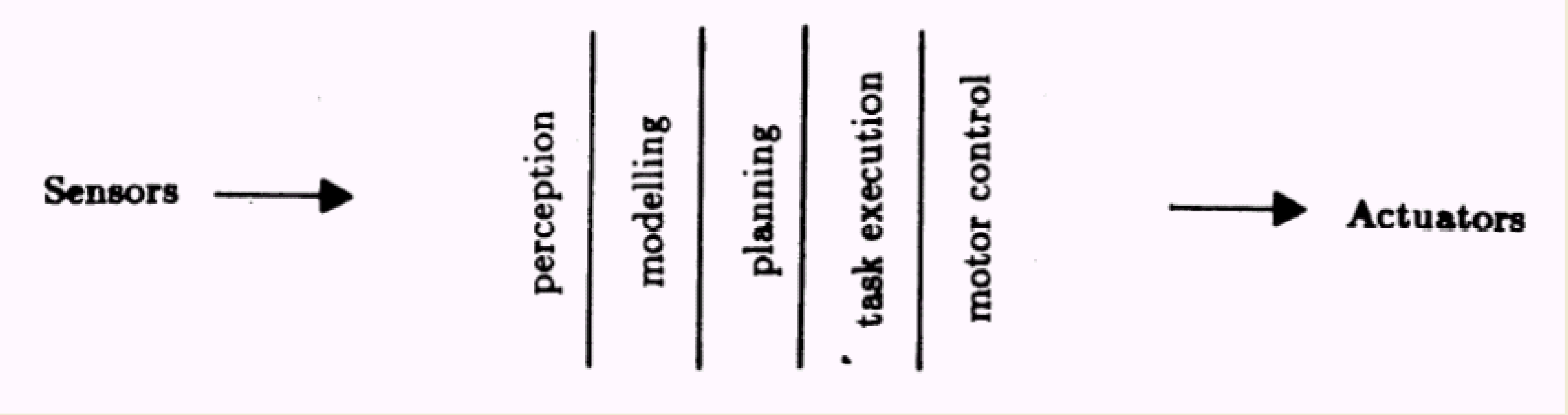
  - However, computer vision is very complex
    - Correspondence problem makes stereo vision even more difficult

Uncertainty in Robot Systems

- Robot systems in unstructured environments have to deal with sensor noise and uncertainty
  - Sensor uncertainty
    - Sensor readings are imprecise and unreliable
  - Non-observability
    - Various aspects of the environment can not be observed
    - The environment is initially unknown
  - Action uncertainty
    - Actions can fail
    - Actions have nondeterministic outcomes

Deliberative
Robot Control Architectures

- In a deliberative control architecture the robot first plans a solution for the task by reasoning about the outcome of its actions and then executes it



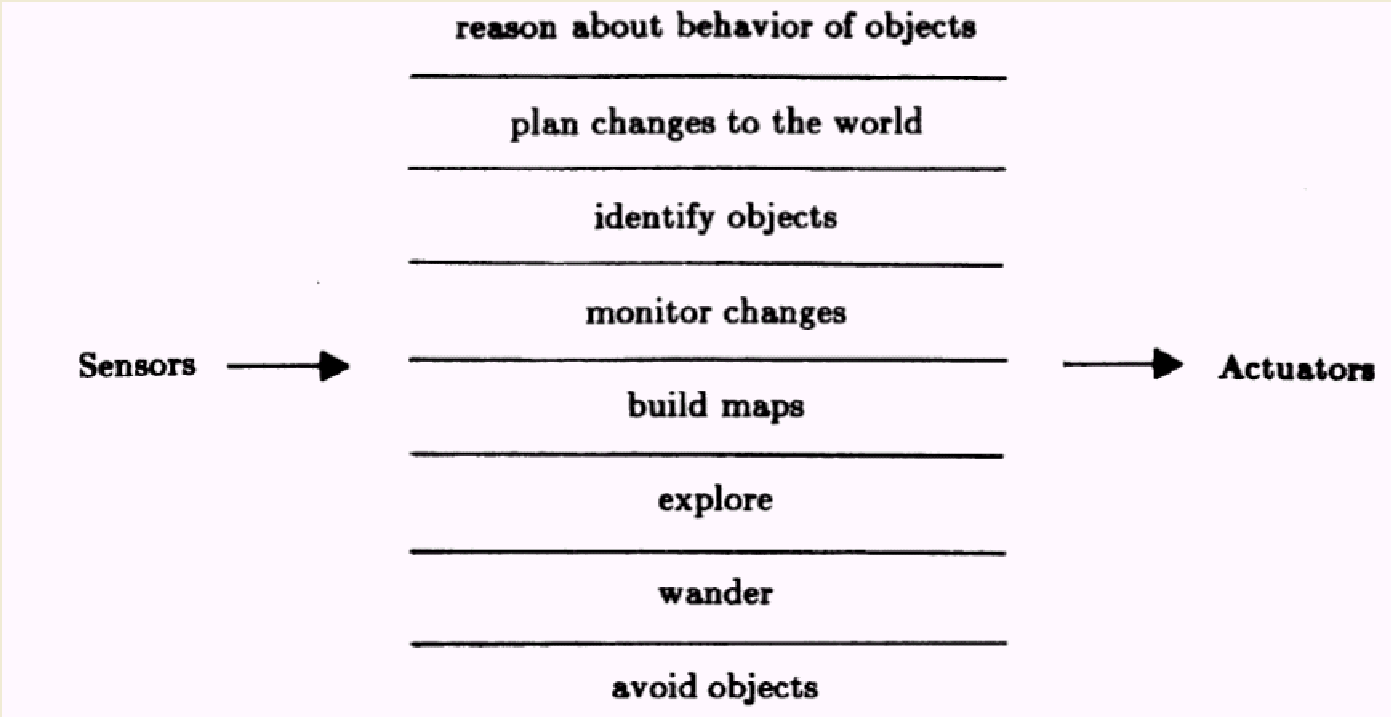
  - Control process goes through a sequence of sencing, model update, and planning steps

Deliberative Control Architectures

- Advantages
  - Reasons about contingencies
  - Computes solutions to the given task
  - Goal-directed strategies
- Problems
  - Solutions tend to be fragile in the presence of uncertainty
  - Requires frequent replanning
  - Reacts relatively slowly to changes and unexpected occurrences

Behavior-Based Robot Control Architectures

- In a behavior-based control architecture the robot's actions are determined by a set of parallel, reactive behaviors which map sensory input and state to actions.

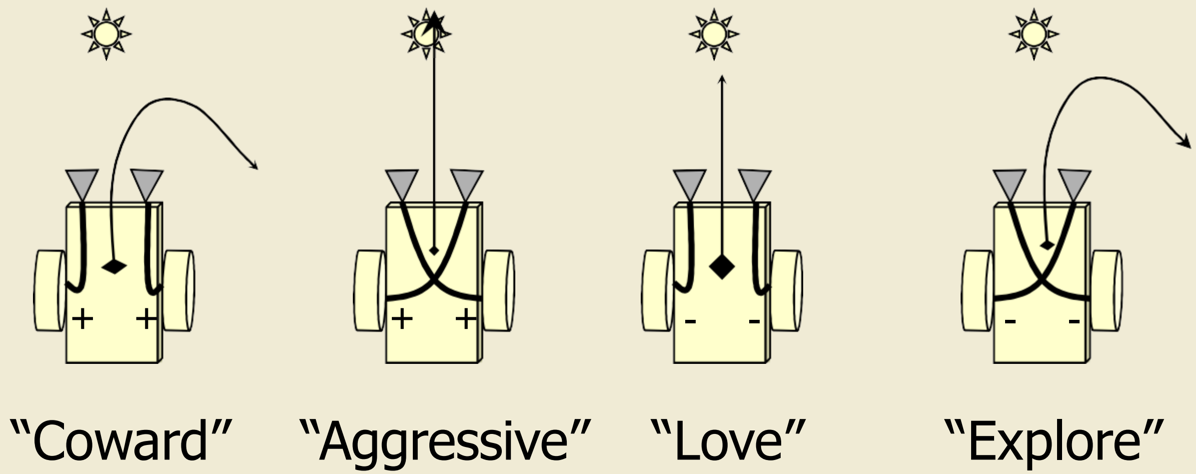


Behavior-Based Robot Control Architectures

- Reactive, behavior-based control combines relatively simple behaviors, each of which achieves a particular subtask, to achieve the overall task.
  - Robot can react fast to changes
  - System does not depend on complete knowledge of the environment
  - Emergent behavior (resulting from combining initial behaviors) can make it difficult to predict exact behavior
  - Difficult to assure that the overall task is achieved

Complex Behavior from Simple Elements: Braitenberg Vehicles

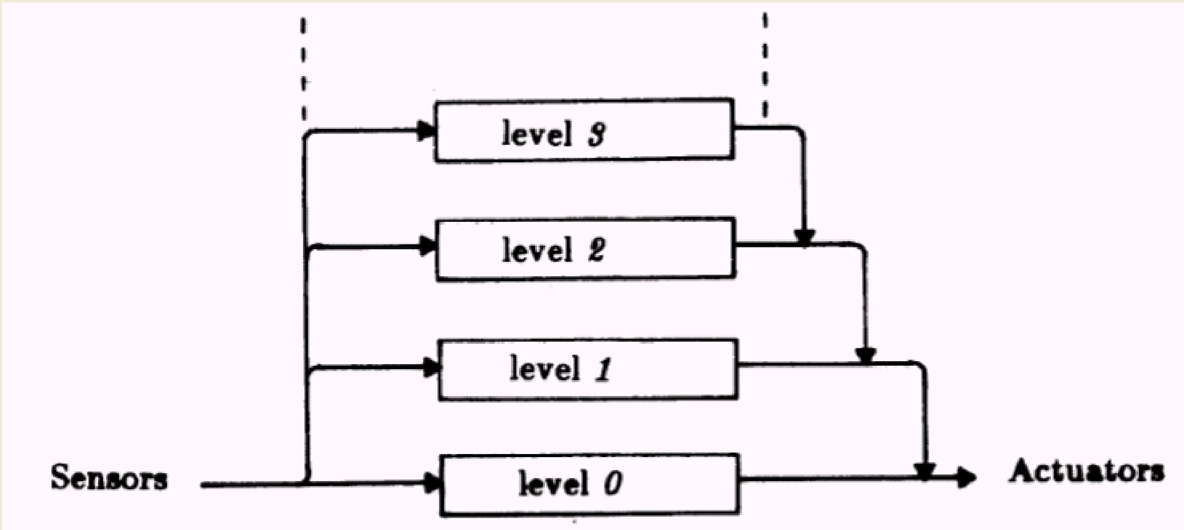
- Complex behavior can be achieved using very simple control mechanisms
  - Braitenberg vehicles: differential drive mobile robots with two light sensors



- Complex external behavior does not necessarily require a complex reasoning mechanism

Behavior-Based Architectures: Subsumption Architecture

- Subsumption architecture: when behaviors have an obvious hierarchy
  – Behaviors are arranged in a strict priority order where higher priority behaviors subsume lower priority ones as long as they are not inhibited.

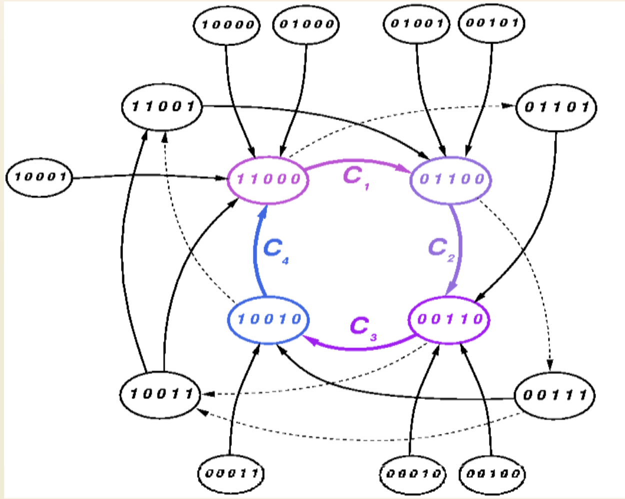


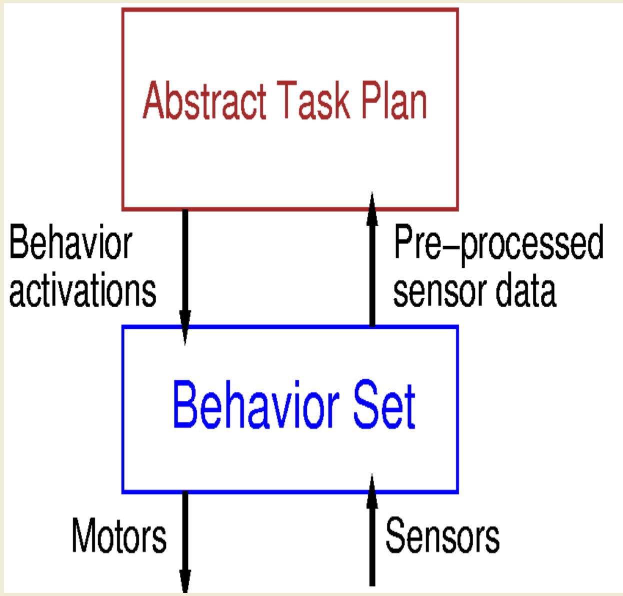
Reactive, Behavior-Based Control Architectures

- Advantages
  - Reacts fast to changes
  - Does not rely on accurate models
    - "The world is its own best model"
  - No need for replanning
- Problems
  - Difficult to anticipate what effect combinations of behaviors will have
  - Difficult to construct strategies that will achieve complex, novel tasks
  - Requires redesign of control system for new tasks

Hybrid Control Architectures

- Hybrid architectures combine reactive control with abstract task planning
  - Abstract task planning layer
    - Deliberative decisions
    - Plans goal directed policies
  - Reactive behavior layer
    - Provides reactive actions
    - Handles sensors and actuators





Hybrid Control Architectures

- Advantages
  - Permits goal-based strategies
  - Ensures fast reactions to unexpected changes
  - Reduces complexity of planning
- Problems
  - Choice of behaviors limits range of possible tasks
  - Behavior interactions have to be well modeled to be able to form plans

Example: Minerva the Tour Guide Robot (CMU/Bonn)

https://www.youtube.com/watch?v=NOhcQCy1Kxs

Example: The Nursebot Project

https://www.youtube.com/watch?v=7lLP5hGqKB8

"Social" Robot Interactions

- To make robots acceptable to average users they should appear and behave “natural”
  - "Attentional" Robots
    - Robot focuses on the user or the task
    - Attention forms the first step to imitation
  - "Emotional" Robots
    - Robot exhibits “emotional” responses
    - Robot follows human social norms for behavior
      - Better acceptance by the user (users are more forgiving)
      - Human-machine interaction appears more “natural”
      - Robot can influence how the human reacts

"Social" Robot Example: Kismet

http://www.ai.mit.edu/projects/cog/Video/kismet/kismet_face_30fps.mpg

"Social" Robot Interactions

- Advantages:
  - Robots that look human and that show "emotions" can make interactions more "natural"
    - Humans tend to focus more attention on people than on objects
    - Humans tend to be more forgiving when a mistake is made if it looks "human"
  - Robots showing "emotions" can modify the way in which humans interact with them
- Problems:
  - How can robots determine the right emotion ?
  - How can "emotions" be expressed by a robot ?

Adaptation and Learning In Autonomous Robots

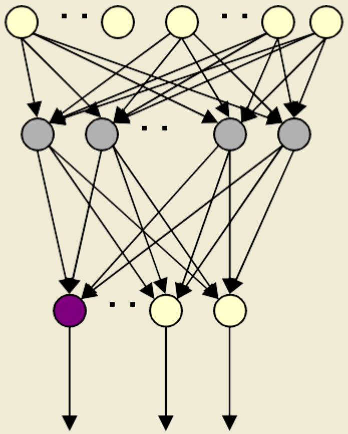
- Learning to interpret sensor information
  - Recognizing objects in the environment is difficult
  - Sensors provide prohibitively large amounts of data
  - Programming of all required objects is generally not possible
- Learning new strategies and tasks
  - New tasks have to be learned on-line in the field
  - Different situations require new strategies even for existing tasks
- Adaptation of existing control policies
  - Goals and paths can change dynamically
  - Changes in the environment have to be perceived and explored

Learning Approaches for Robot Systems

- Supervised learning by teaching
  - Robots can learn from direct feedback from the user that indicates the correct strategy
    - The robot learns the exact strategy provided by the user
- Learning from demonstration (Imitation)
  - Robots learn by observing a human or a robot perform the required task
    - The robot has to be able to “understand” what it observes and map it onto its own capabilities
- Learning by exploration
  - Robots can learn autonomously by trying different actions and observing their results
    - The robot learns a strategy that optimizes reward

Learning Sensory Patterns

- Learning to Identify Objects
  - How can a particular object be recognized ?
    - Programming recognition strategies is difficult because we do not fully understand how we perform recognition
    - Learning techniques permit the robot system to form its own recognition strategy
  - Supervised learning can be used by giving the robot a set of pictures and the corresponding classification
    - Neural networks
    - Decision trees



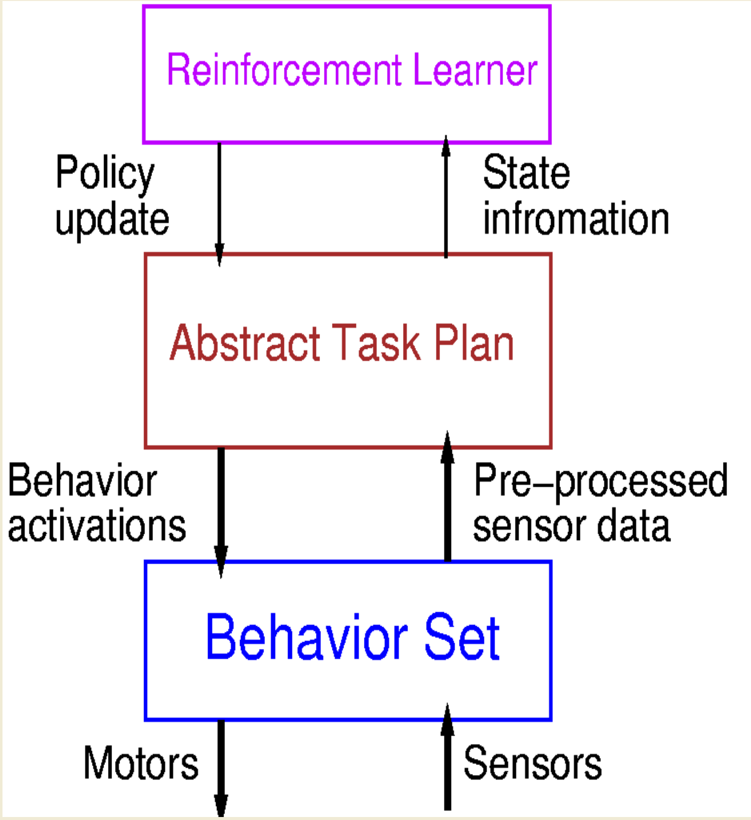
Chair

Learning Task Strategies by Experimentation

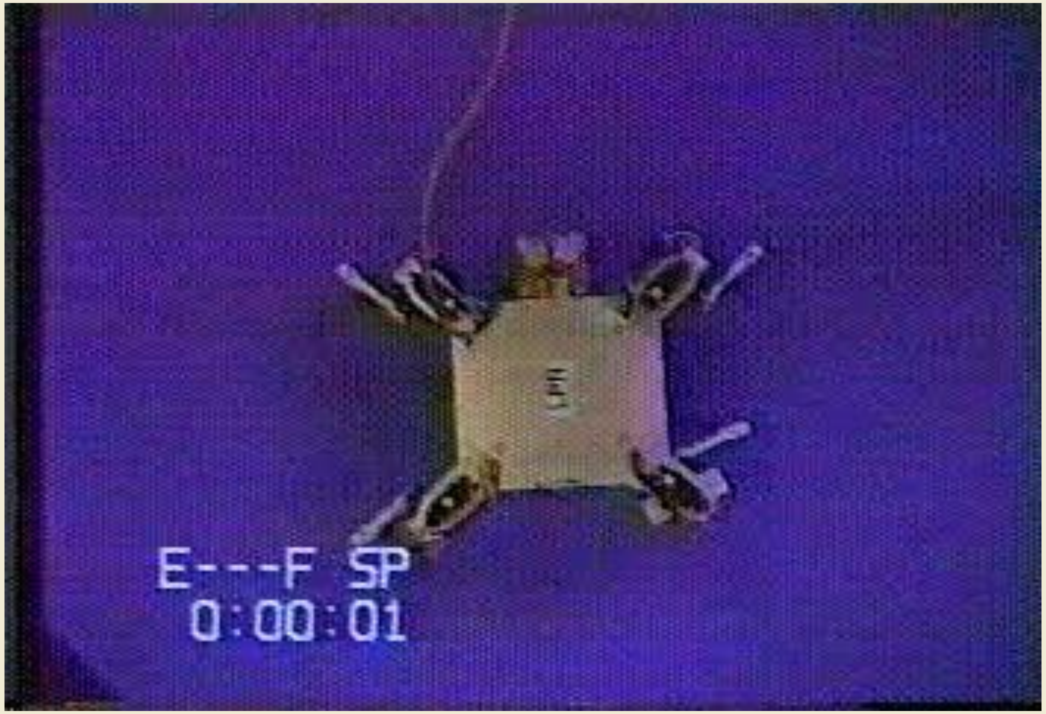
- Autonomous robots have to be able to learn new tasks even without input from the user
  - Learning to perform a task in order to optimize the reward the robot obtains (Reinforcement Learning)
    - Reward has to be provided either by the user or the environment
      - Intermittent user feedback
      - Generic rewards indicating unsafe or inconvenient actions or occurrences
    - The robot has to explore its actions to determine what their effects are
      - Actions change the state of the environment
      - Actions achieve different amounts of reward
    - During learning the robot has to maintain a level of safety

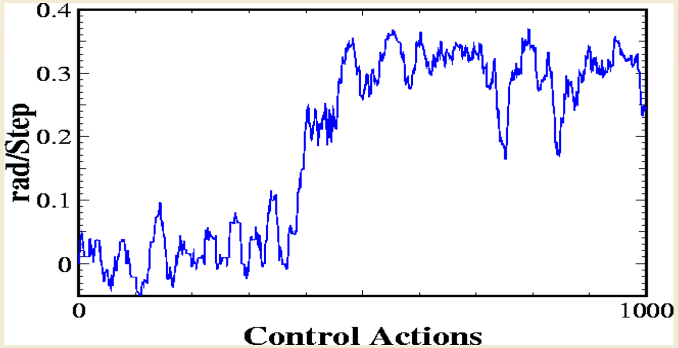
Example: Reinforcement Learning in a Hybrid Architecture

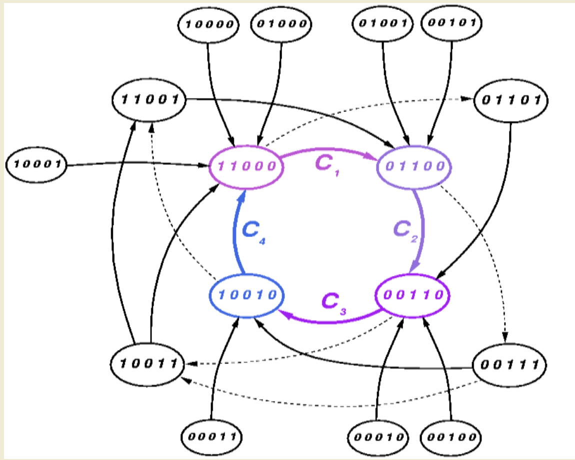
- Policy Acquisition Layer
  - Learning tasks without supervision
- Abstract Plan Layer
  - Learning a system model
  - Basic state space compression
- Reactive Behavior Layer
  - Initial competence and reactivity



Example Task: Learning to Walk







Conclusions

- Robots are becoming important for work, transport and social interaction
  - Automation, self-driving vehicles, drones
  - Providing physical services and assistance
- For robotic systems to achieve this objective they need particular capabilities
  - Autonomous control systems
  - Simple and natural human-robot interface
  - Adaptive learning capabilities
  - Remain safe during operation
- While much progress has been made, no complete solutions have yet been devised
  - Never in history have the rewards for the development of autonomous machines been so great and the impact so disruptive