Presentazione Corso

- Corso da 6 crediti (48 ore)
- Orario di Ricevimento: Mercoledì, 15:30-17:30 (teleconf)
- e-mail: alberto.finzi@unina.it
- Pagina-web: http://wpage.unina.it/alberto.finzi/didattica/IRob/
- Orario:
  - Martedì 14:00 16:00 - team
  - Giovedì 11:00 13:00 - team

Obiettivi del Corso

- Basi teoriche e strumenti concettuali per la progettazione di **sistemi robotici intelligenti**
  - Comportamento autonomo e/o interattivo
  - Capaci di operare in modo finalizzato, flessibile ed adattivo
  - Ambiente reale non strutturato
  - Funzioni cognitive (percezione, pianificazione, apprendimento, etc.)
- Robotica ed Intelligenza Artificiale
  - Embodied Artificial Intelligence (Embodied Agents)
  - Metodi AI per la Robotica
- Tematiche:
  - Robotica Autonoma, Robotica Cognitiva, Robotica di Servizio, Robotica Collaborativa e Sociale

Programma

- **Robotica Probabilistica**
  - Metodi statistici in Robotica
  - Metodi per la Robotica Mobile
    - Localizzazione, mapping, navigazione, pianificazione di percorso
  - Pianificazione probabilistica
  - Apprendimento per rinforzo

- **Robotica Autonoma e Cognitiva**
  - Architetture Robotiche
  - Middleware e integrazione (introduzione a ROS)
  - Pianificazione di Task
  - Sistemi esecutivi
  - Architetture Cognitive
  - Robotica Collaborativa

Materiale Didattico

- Slides, papers, on-line references
- Murphy R.R. - Introduction to AI robotics - MIT Press
- Probabilistic Robotics, Sebastian Thrun, Wolfram Burgard and Dieter Fox, MIT Press
- Altri testi da consultare (disponibili on-line):
  - Planning Algorithms, Steven M. LaValle Robot Planning
  - Automated Planning and Acting, Malik Ghallab, Dana Nau, Paolo Traverso AI Planning
  - Richard S. Sutton and Andrew G. Barto Reinforcement Learning: An Introduction

Esame

- Modalità di accertamento del profitto:
  - Presentazione e discussione papers
  - Progetto
    - Gruppi di uno o due studenti
  - Presentazione e discussione progetto

Intelligent Robots

- **Intelligence:**
  - Latin: Intelligentia, intelligere
    - Etimology: intus + ligere or inter + ligere
    - faculty of understanding, comprehension (high-level cognition)

- **Robots:**
  - Czech: Robota (work) and robotnik (worker)
  - Karel Čapek in his play R.U.R. (Rossum's Universal Robots), published in 1920 (first performance on January 25, 1921 in Pargue)
  - “Robotics” by Isaac Asimov in science fiction short-story "Liar!“ (three Laws of Robotics), 1941

Autonomous Robots

- **Autonomous:**
  - Greek: Automaton (auto + matos)
    - auto: self
    - matos: thinking, animated, willing

- **Robots:**
  - Czech: Robota (work) and robotnik (worker)
  - Karel Čapek in his play R.U.R. (Rossum's Universal Robots), published in 1920 (first performance on January 25, 1921 in Pargue)
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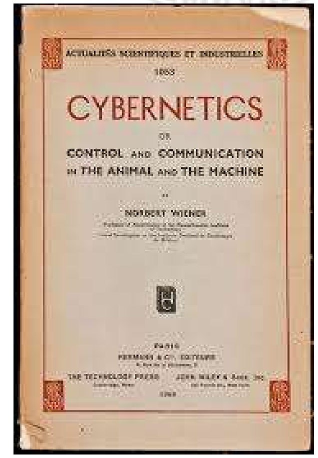
self-willed … but task-oriented

Cybernetics

1948 Norbert Wiener formulated the principles of cybernetics



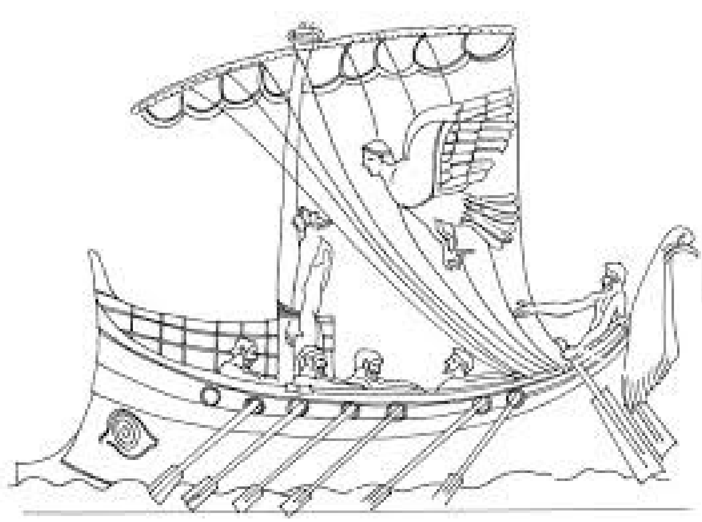
Wiener, Cybernetics

- Studied regulatory systems and their application to control (antiaircraft gun)

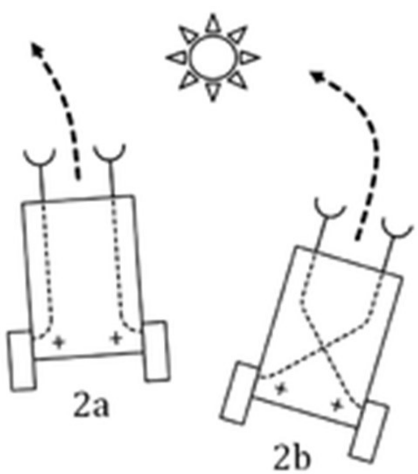
- “it has long been clear to me that the modern ultra-rapid computing machine was in principle an ideal central nervous system to an apparatus for automatic control; and its input and output need not be in the form of numbers or diagrams, but might very well be, respectively, the readings of artificial sensors such as photoelectric cells or thermometers, and the performance of motors or solenoids”.

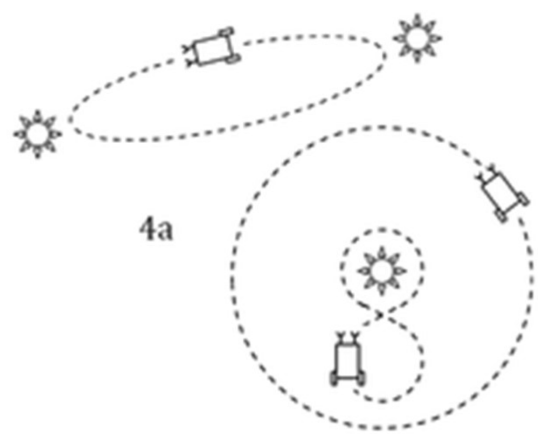
[Electronics, 1949]

- “the scientific study of control and communication in the animal and the machine”
- From greek κυβερνητική (kybernetike) "governance", κυβερνάω (kybernao), "to steer, navigate or govern", κυβέρνησις (kybernesis), "government", κυβερνήτης (kybernetes), governor or the captain



- Robotics and Cybernetics
  - Control feedback:
    - Sensorimotor processes, interaction with the environment, body
  - Emergent behavior:
    - Complexity from simple systems (*Veicoli pensanti di V.* Braitenberg)





Artificial Intelligence

- **Artificial Intelligence**:
  - “The science of making machines act intelligently” (Murphy)
  - “the theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making” (Oxford Dic.)
  - “the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings” (Britannica Enc.)

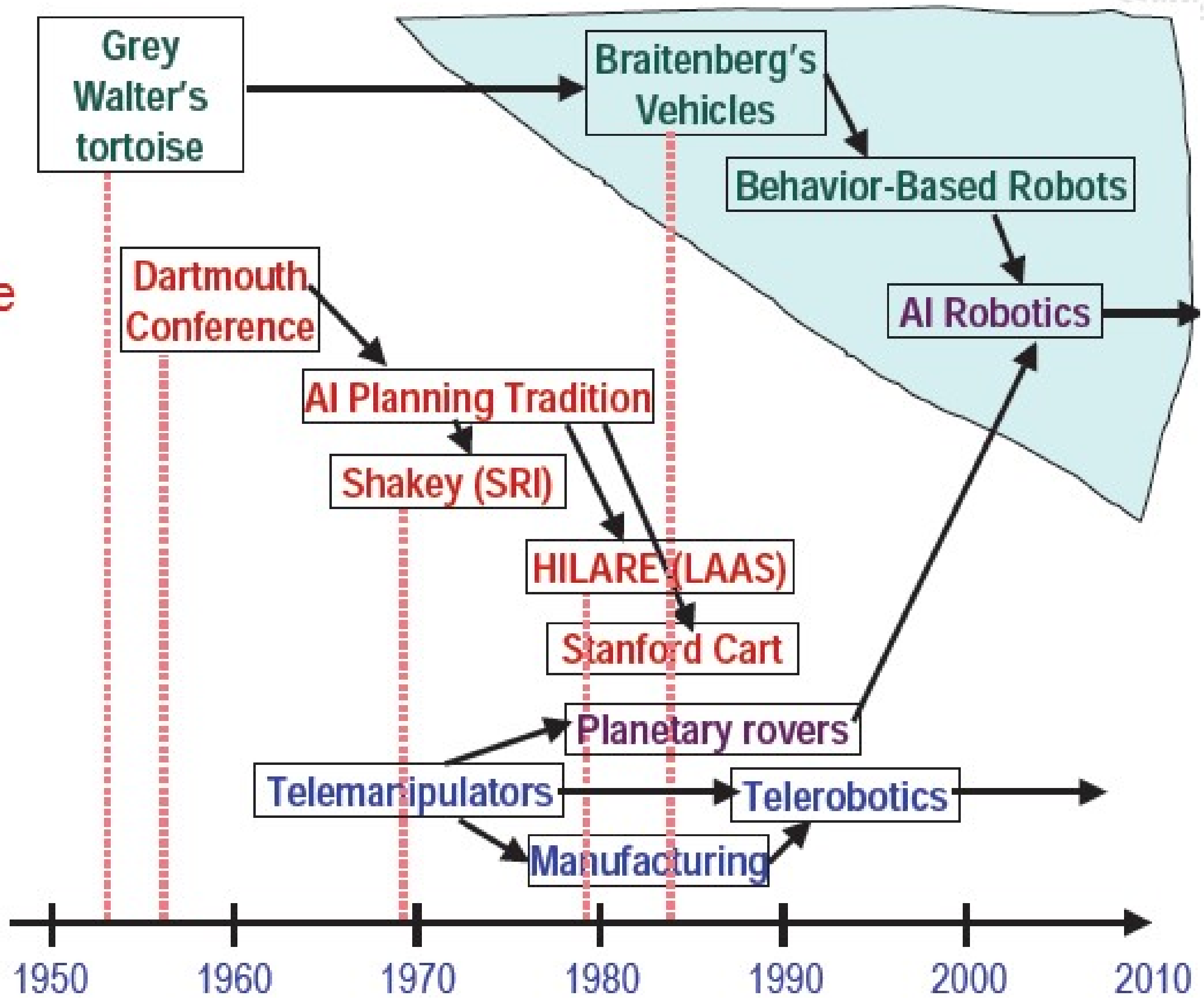
- **1956 Dartmouth College workshop**:
  - Organized by John McCarthy
  - Proposal:
    - “The study is to proceed on the basis of the conjecture that every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it. An attempt will be made to find how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved for humans, and improve themselves.” (J. McCarthy, M. Minsky, N. Rochester and C. Shannon)

AI and Robotics

- **Agent**
  - “An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors” (Norvig and Russell)
  - “Agency is a concept in AI that allows researchers to discuss the properties of intelligence without discussing the details of how the intelligence got in the particular agent” (Murphy)
- **Rational Agent**
  - “A rational agent is one that does the right thing” (Russell & Norvig)
- **Intelligent Agent**
  - “a system that perceives its environment and takes actions which maximize its chances of success” (Russell & Norvig)
  - Software Agent (Softbot) or Physical Agent (Robot)
- **Intelligent Robot**
  - “Physically situated intelligent agent ” (Murphy)

Autonomous Robots

- Cybernetics
- Artificial Intelligence
- Robotics



Cognitive Science and Robotics

- Multidisciplinary investigation of mind and the associated cognitive processes
  - Computational metaphore (AI):
    - Knowledge representation and calculus
  - Embodied Cognitive Science:
    - Cognition in action
    - Relevance of the body and interaction with the environment
  - Cognitive Robotics:
    - Robots endowed with cognitive capabilities

- Cognitive Architectures
  - Unified Theory of Cognition [Newell 1990]

- Cognitive Robotics
  - Embodied AI
    - Robots able to perceive, reason, learn, deliberate, plan, act, interact, etc.
  - Autonomous Robots and Cognitive Architectures
    - Robotics, cognitive framework, cognitive models, computational models

- <u>Autonomous Robots</u>:
  - robots that can perform tasks in <u>unstructured</u> environments without <u>continuous</u> human guidance

- Industrial robots (fixed-base):
  - fast, accurate, ripetitive … but limited in workspace

- To operate in the real world (open world), robots must be able to cope with:
  - large, open, unstructured, dynamic, uncertain, partially observable environments, populated, ect. …

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Autonomy

- "Automation is about physically-situated tools performing highly repetitive, pre-planned actions for well-modeled tasks under the closed world assumption" (Murphy)

- "Autonomy is about physically-situated agents who not only perform actions but can also adapt to the open world where the environment and tasks are not known a priori by generating new plans, monitoring and changing plans, and learning within the constraints of their bounded rationality" (Murphy)

Closed World vs Open World

- **Closed World**
  - Everything relevant is known *a priori* (no surprises)
  - Everything relevant can be completely modeled
  - If world is modeled accurately enough, **can create stable control loops to respond to all expected situations**
  - If world is controlled, **can minimize or eliminate sensing**

- **Open World**
  - Models may be available, but are only partially (and unpredictably) correct
  - Must be able to **sense relevant aspects** of the world in order to **dynamically adapt actions** (e.g., act as an agent)

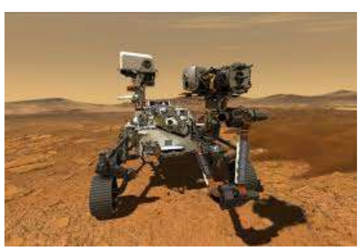
Closed World vs Open World

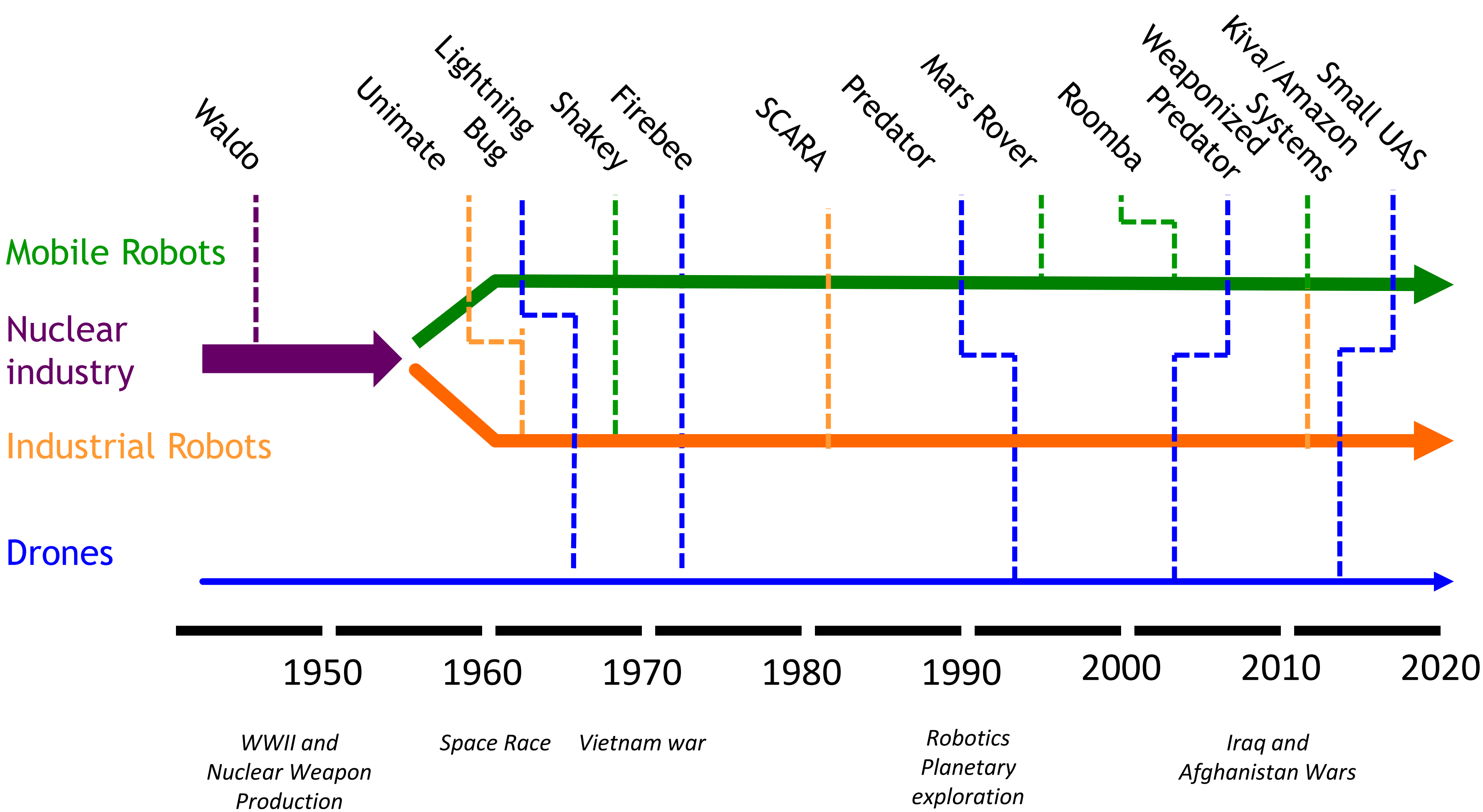
- **Closed World**
  - <u>Small set of repetitious tasks</u>
    - Focus is on stable control loops
    - Control

Automation

- **<u>Open World</u>**
  - <u>Variety of tasks</u> while <u>operating in dynamic environments</u>
    - Focus is on Artificial Intelligence
    - Control and Governance

Autonomy





Waldo
Unimate
Lightning Bug
Shakey
Firebee
SCARA
Predator
Mars Rover
Roomba
Weaponized Predator
Kiva/Amazon Systems
Small UAS
Mobile Robots
Nuclear industry
Industrial Robots
Drones
1950
1960
1970
1980
1990
2000
2010
2020
WWII and Nuclear Weapon Production
Space Race
Vietnam war
Robotics Planetary exploration
Iraq and Afghanistan Wars

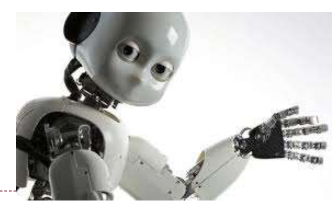
Autonomous Robots

- Autonomous Robotics Systems:
  - Field Robotics:
    - Agricultural, exploration, search and rescue, etc.
  - Service Robotics:
    - Domestic, logistic, health, etc.
  - Social Robotics:
    - Assistive, entertainment, etc.





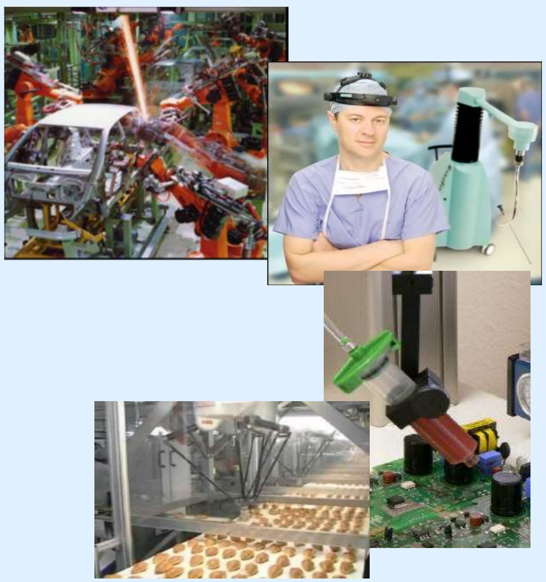




Autonomous Robots

Structured, controlled	Unstructured, unmanned, autonomous	Unstructured, proactive, interactive

Industrial



Manufacturing
Mining
Surgery

Field

Aerospace
Underwater
Rescue

Service

Home
Entertainment
Health care

Autonomous Robots

1. **Teleoperation**. A human operator controls each movement, each machine actuator change is specified by the operator.

2. **Supervisory**. A human specifies general moves or waypoints (moveTo) and the machine decides specific movements of its actuators.

3. **Task-level autonomy**. The operator specifies tasks, while the robot manages itself to complete it.

4. **Full autonomy**. The machine will create and complete all its tasks without human interaction.

5. **Long-term autonomy.** The machine is intrinsically motivated, endowed with motivational system, goal management, lifelong learning mechanisms, etc.

Autonomous Robots

- **Taskability**: ability to achieve multiple tasks described at an abstract level.
- **Autonomy**: ability to carry out actions by itself
  - **Adaptability:** modify own behavior according to current goal and execution context as perceived.
  - **Reactivity**: take into account situations and events with time bounds compatible with the correct and efficient achievement of goals and with environment dynamics.
- **Consistent behavior**: reactions to events guided by the objectives of the task (not "pure reflex").
- **Robustness/dependability**: ability to cope with failures and critical environmental changes.
- **Reconfigurability and evolvability**: possibility to add (or "grow") new components and abilities. Scalability, **open-endedness**, ease of development.

- Automotive:
  - Driveless car
    - Mapping, localization, vision/LiDAR-based detection, avoidance, path planning, navigation, decision making, etc.

  - Assisted Driving
    - Autopilot, cruise control, vision-based detection, avoidance, alerting, HMI, etc.

- Levels of driving automation/autonomy:
  - Human monitoring:
    - Level 0 – (no automation) manually controlled
    - Level 1 - (hands on) driver assistance (e.g. cruise control)
    - Level 2 - (hands off) partial driving automation (advanced driver assistance systems)
  - System monitoring:
    - Level 3 - (eyes off) conditional automation (self-driving in ideal conditions)
      - Environment interpretation, monitoring, decision making
    - Level 4 - (mind off) autonomous driving, with human on-board
      - All driving tasks can be autonomous, human should interact
    - Level 5 - (steering wheel optional) self-driving car
      - The human presence is not required

- Search & Rescue Robotics:
  - Robotic system designed for searching and rescuing people
  - Urban (earthquake, dangerous places, etc.), not Urban (sea, mountains, harsh terrains, etc.)
  - Robots:
    - Ground
    - Aerial
    - Marine
    - …

Search and Rescue Robotics

- Multimodal Human-Robot Interaction for Multi-UAVs Control in SHERPA





Mixed **ground** and **aerial** robotic platform to support **search and rescue** activities in the alpine scenario

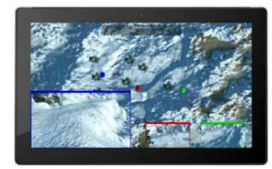
The human rescuer is the "busy genius" working in team with the ground vehicle and with the aerial platforms"

"able to provide sketchy, though high-value, inputs towards the achievement of the team goal."

Coordinator: Prof. Marconi, UNIBO

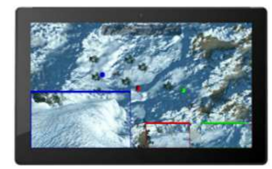
Search and Rescue Robotics

- Drones in the Alps

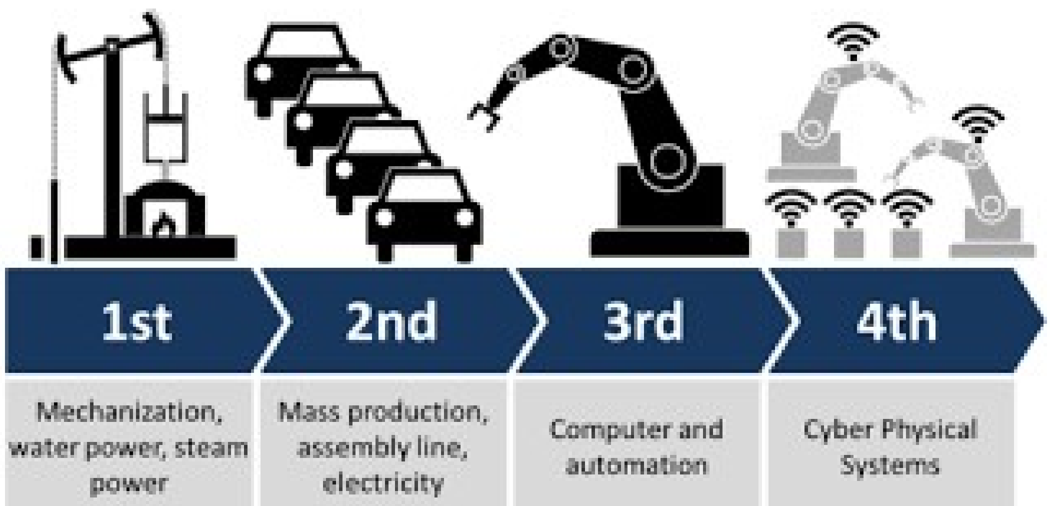


Search and Rescue Robotics

- Drones in the Alps



- Robot co-worker (Cobot, Industry 4.0)
  - Smart production, advanced manufacturing solutions
  - Customization of products, flexibilized mass-production



- Robot co-worker
  - Safe physical and cognitive human-robot interaction …
  - Human monitoring
  - Intention recognition
  - Cognitive/physical interaction
  - Flexible and interactive task execution
  - Multimodal comunication and dialogue
  - Cooperative task execution
  - Turn taking
  - Mixed-initiative planning and execution
  - Plan/task/action recovery/repair
  - Task teaching
  - Learning by demonstration

Robot Co-worker

- Safe and adaptive …

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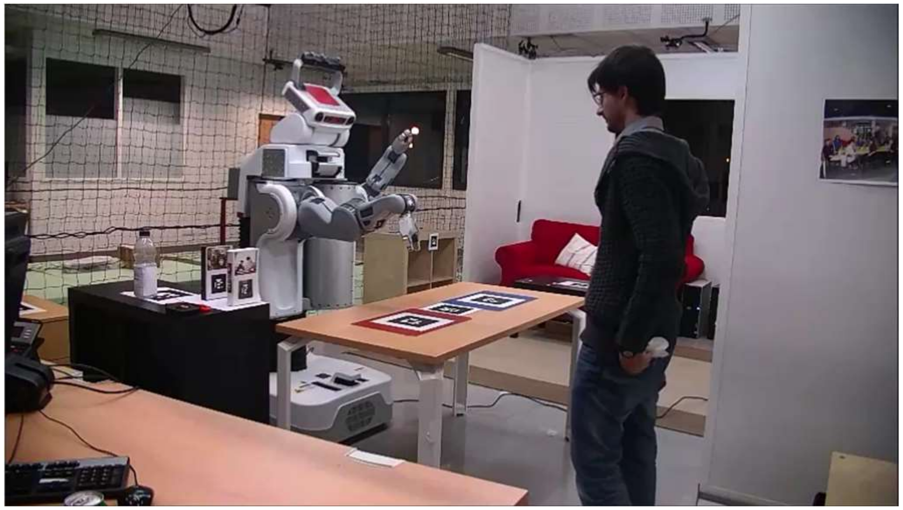
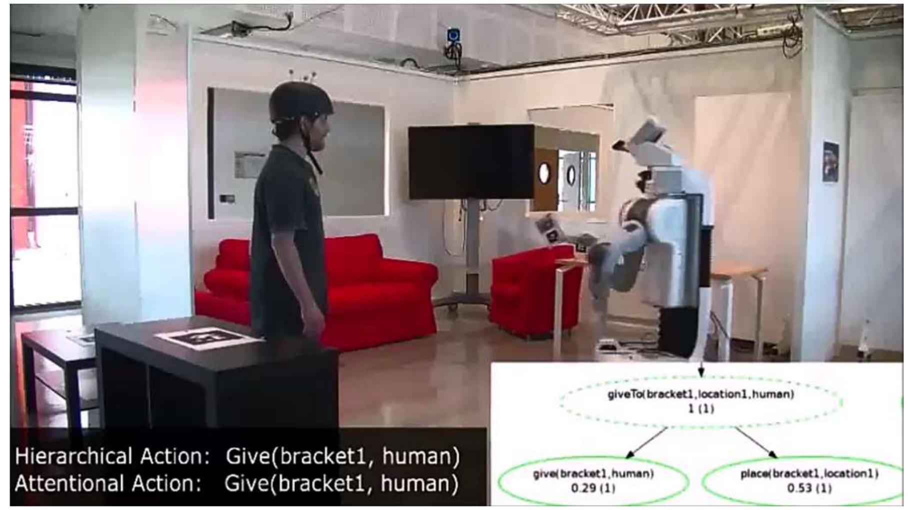
Autonomous Robots



Multimodal Interaction

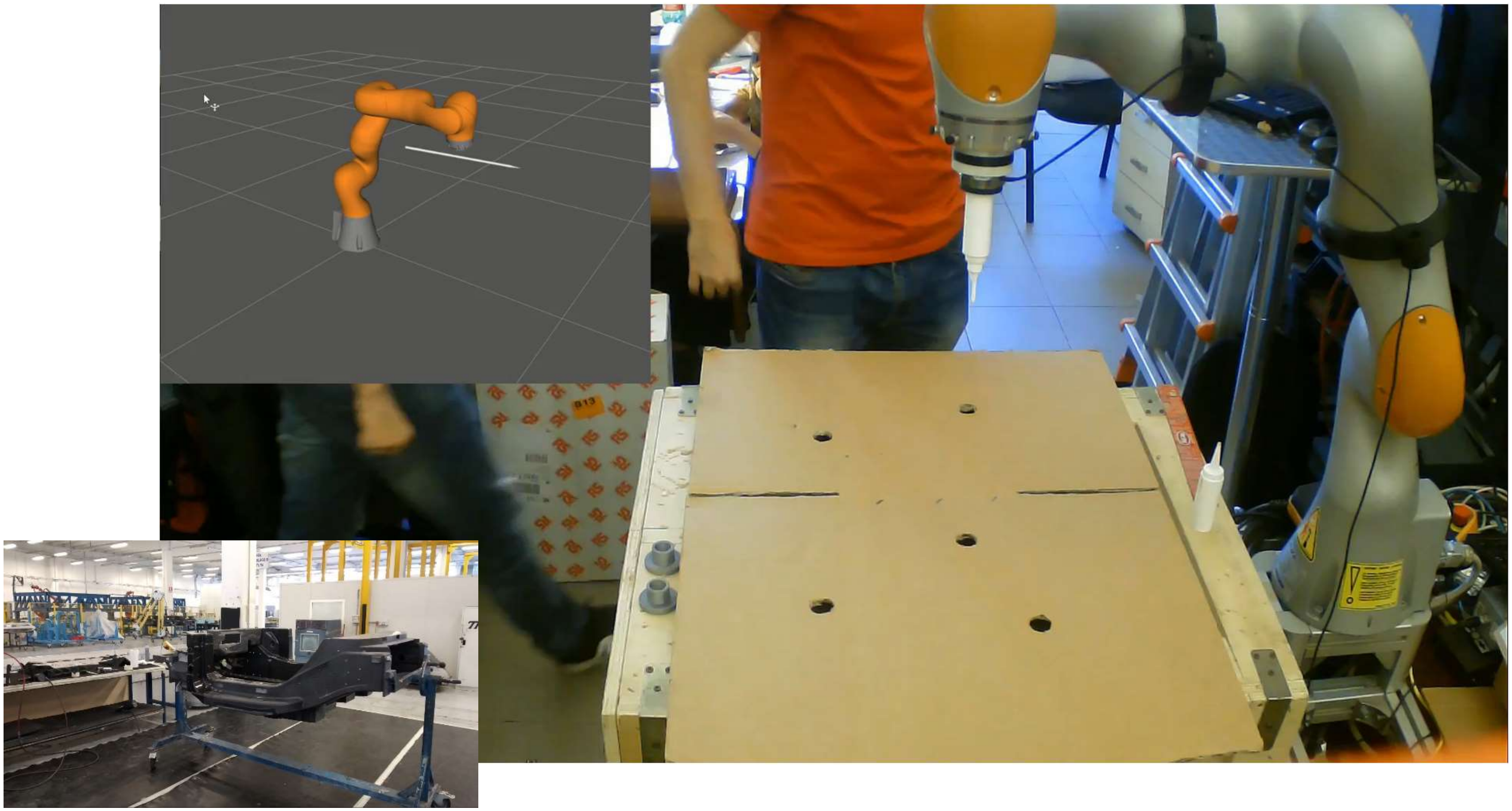


Unexpected Events

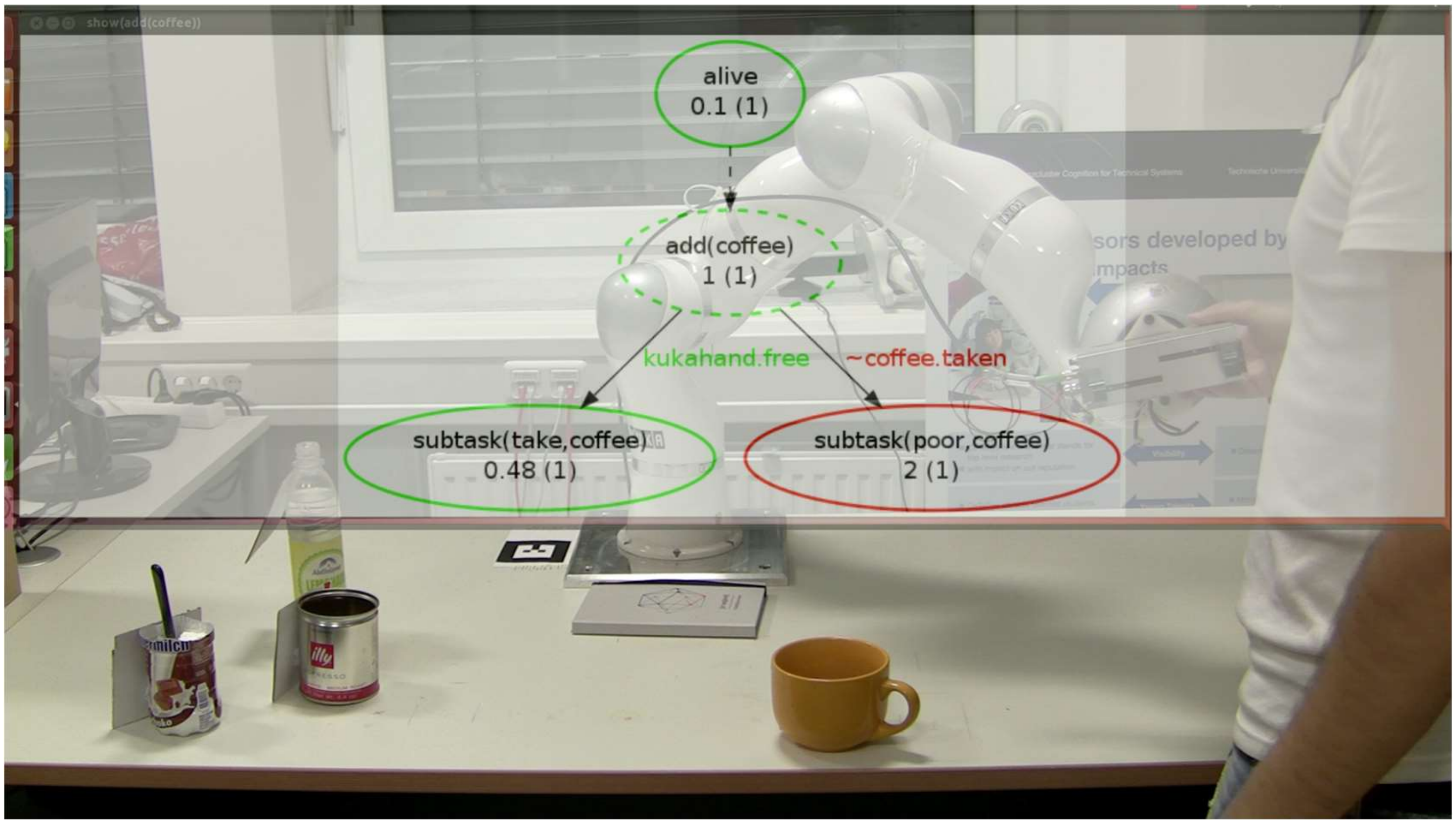
ICOSAF project: Hand Guidance

Integrated and collaborative systems for the intelligent factory
PON – Fondi Strutturali EU (2018-2021)

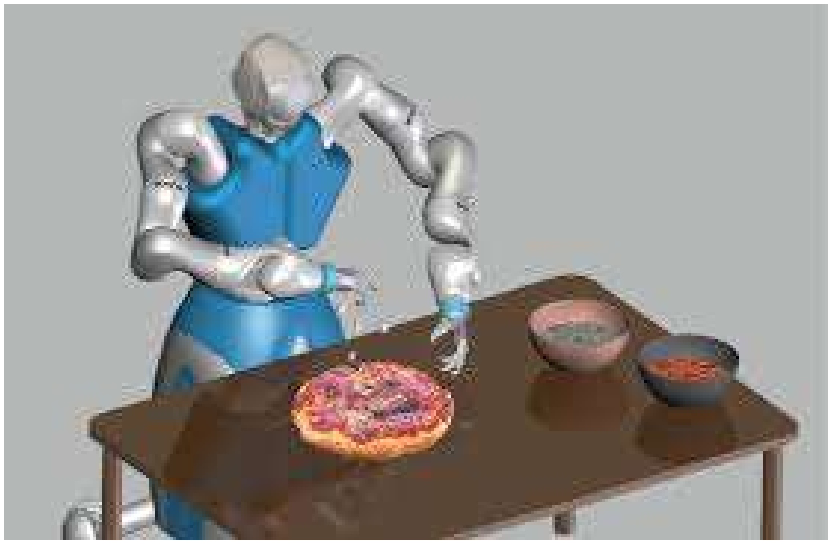
- Hand-guidance and co-manipulation:



- Multimodal interaction and learning by demonstration

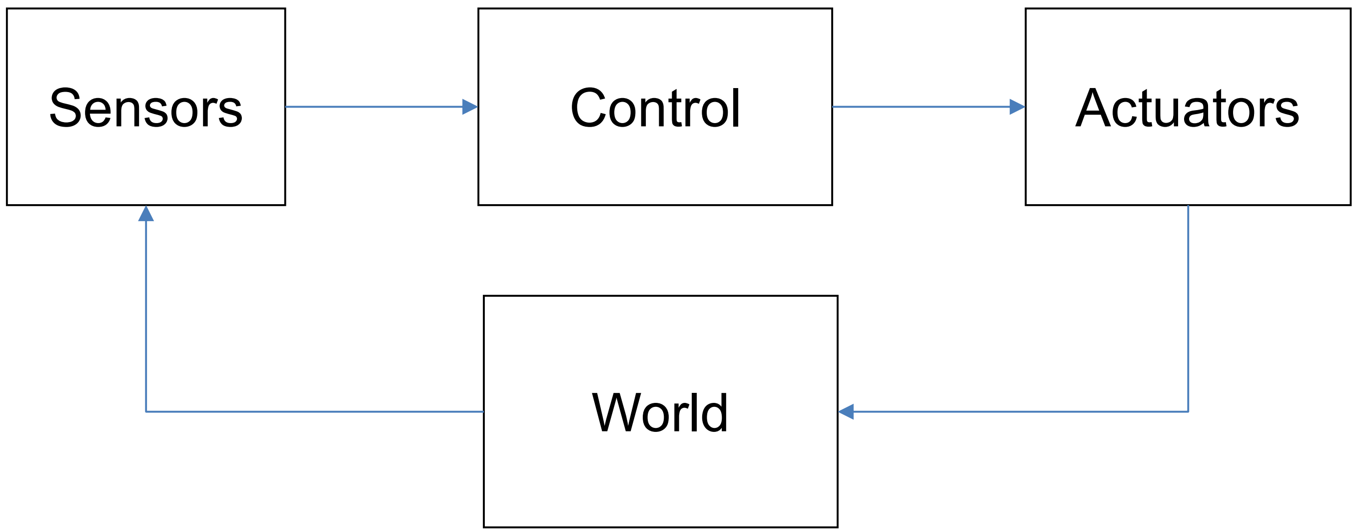


- RObotic DYnamic MANipulation
  - Unified framework for dynamic manipulation of non-prehensile non-rigid or deformable objects (ERC, PI Prof. Bruno Siciliano)

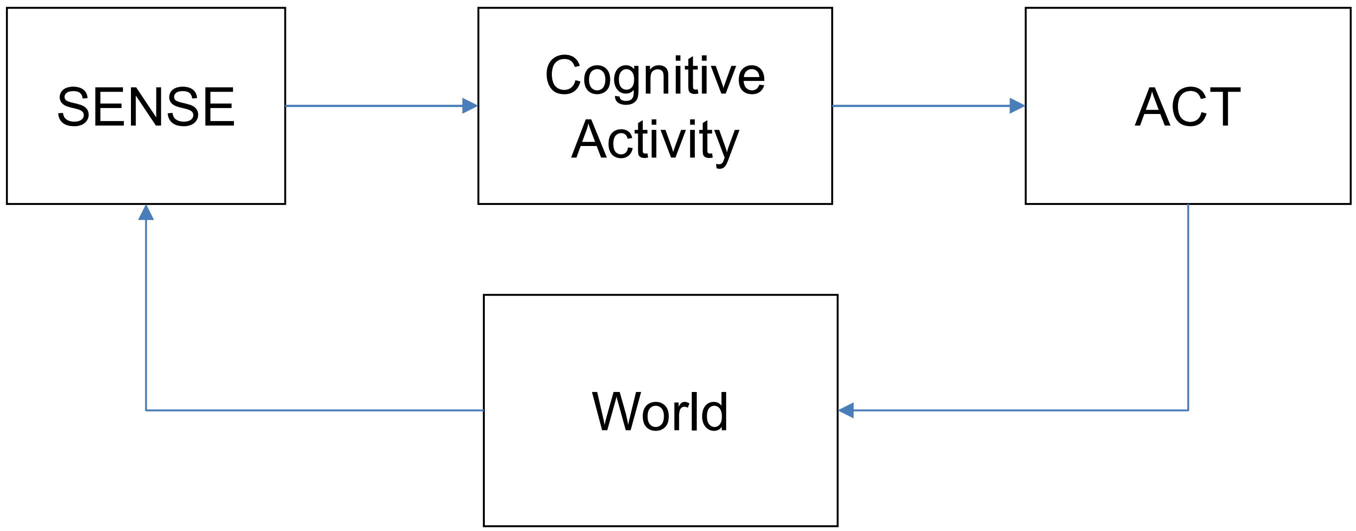


- Robots will allow a smarter shelf refilling
- **R**obotics **E**nabling **F**ully-**I**ntegrated **L**ogistics **L**ines for **S**upermarkets — **REFILLS** (H2020 PI Prof. Bruno Siciliano)

- Control Cycle



- Control Cycle
  - Perception, situation assessment, planning, decision, learning, acting
  - Primitives: SENSE, PLAN, ACT, LEARN
  - Can be complex



Architectures and Paradigms

- Architecture:
  - Set of guiding principles and constraints for organizing the robot components
- Primitives:
  - Sense, Plan, Act, Learn
- Robotic paradigms
  - relationship among primitives

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

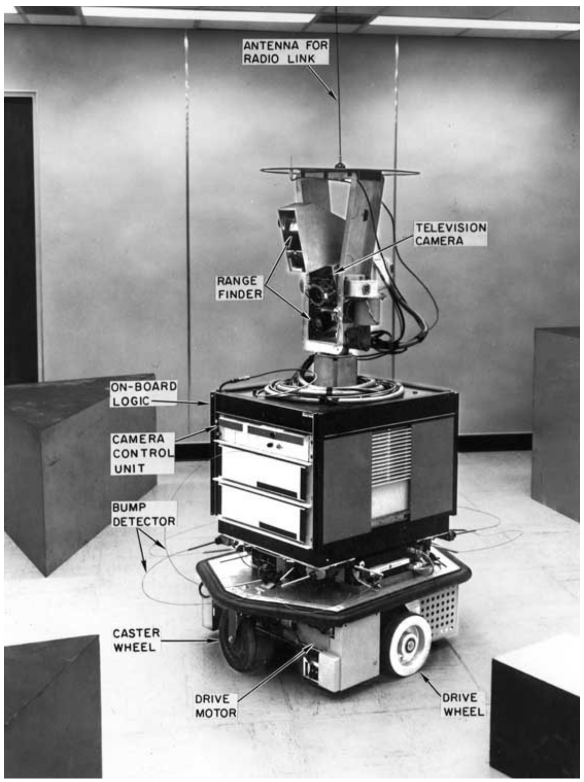
Probabilistic Robotics (since mid-90's)
- seamless integration of models and sensing
- inaccurate models, inaccurate sensors

Autonomous Robots: Paradigms

- Classic Robotics (AI '70):
  - Model-based (representation = world), symbolic, no sensing, only reasoning
- Reactive Robotics (Ethology '80):
  - No models (world is the model), reactive: sense-act (insects-like)
- Hybrid Architectures (Agents '90):
  - Model-based (rep. abstract, but fine) + reactive (3T architectures)
- Probabilistic Robotics (Mobile Robotics '90):
  - Approximate/probabilistic models (rep. != world), actuators not reliable, sensors not accurate;
  - Sensors/Actuators models tight integration.

Shakey the Robot

- Shakey the robot
  - First AI-based robot
    - “The world’s first autonomous robot to move around”
    - Developed at SRI International from 1966 to 1972



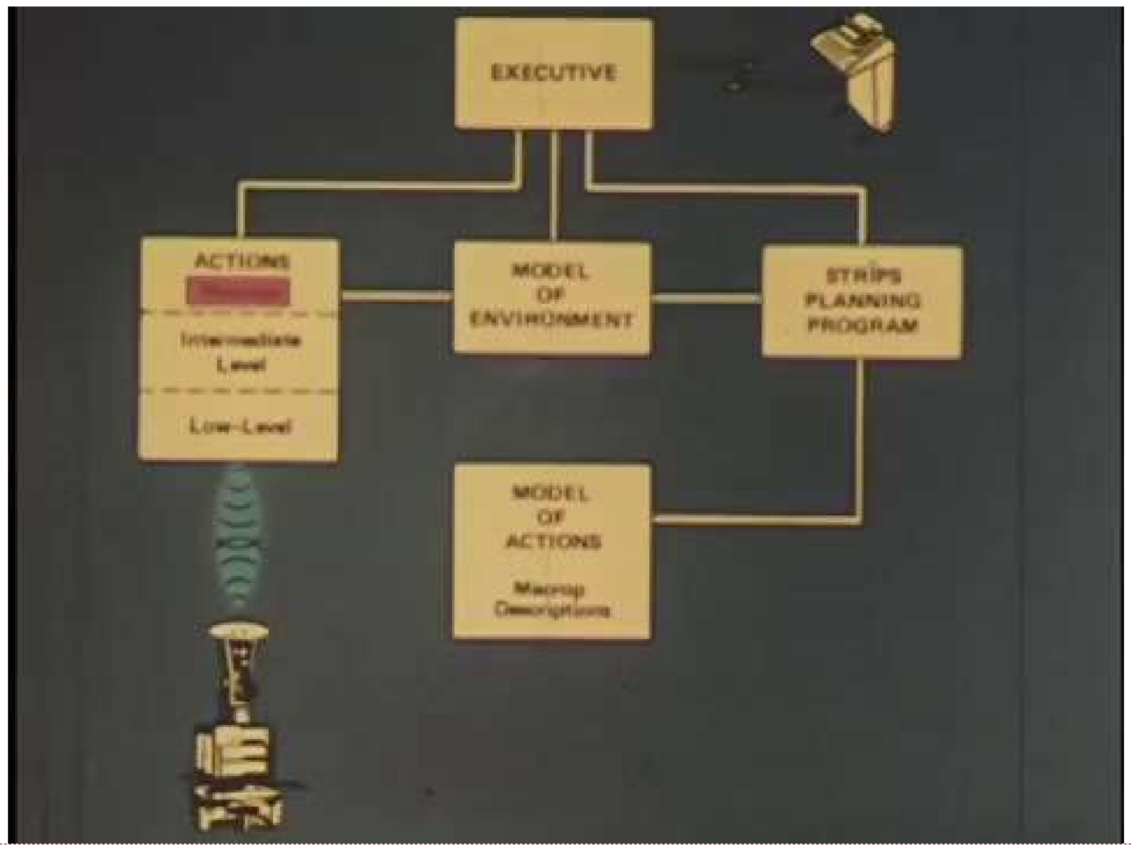
- Remote controlled by a computer
- Reasoning with very selective spatial data
- Edge-based processing of camera and laser range finder measurements
- Generated Plans involving moving from place to place and pushing blocks to achieve a goal
- Deliberative

Shakey the Robot

- Shakey the robot
  - Perception, knowledge representation, reasoning, task and path planning, localization and navigation

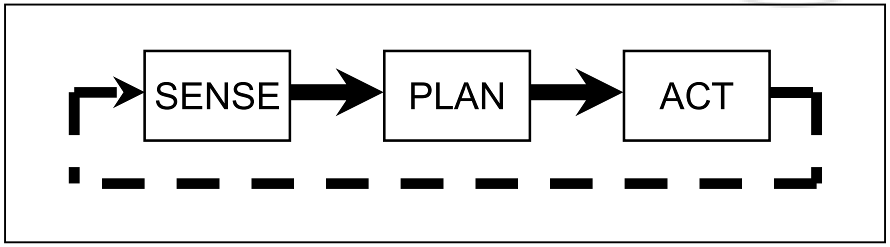
Shakey the Robot

- Shakey the robot
  - Perception, knowledge representation, reasoning, task and path planning, localization and navigation

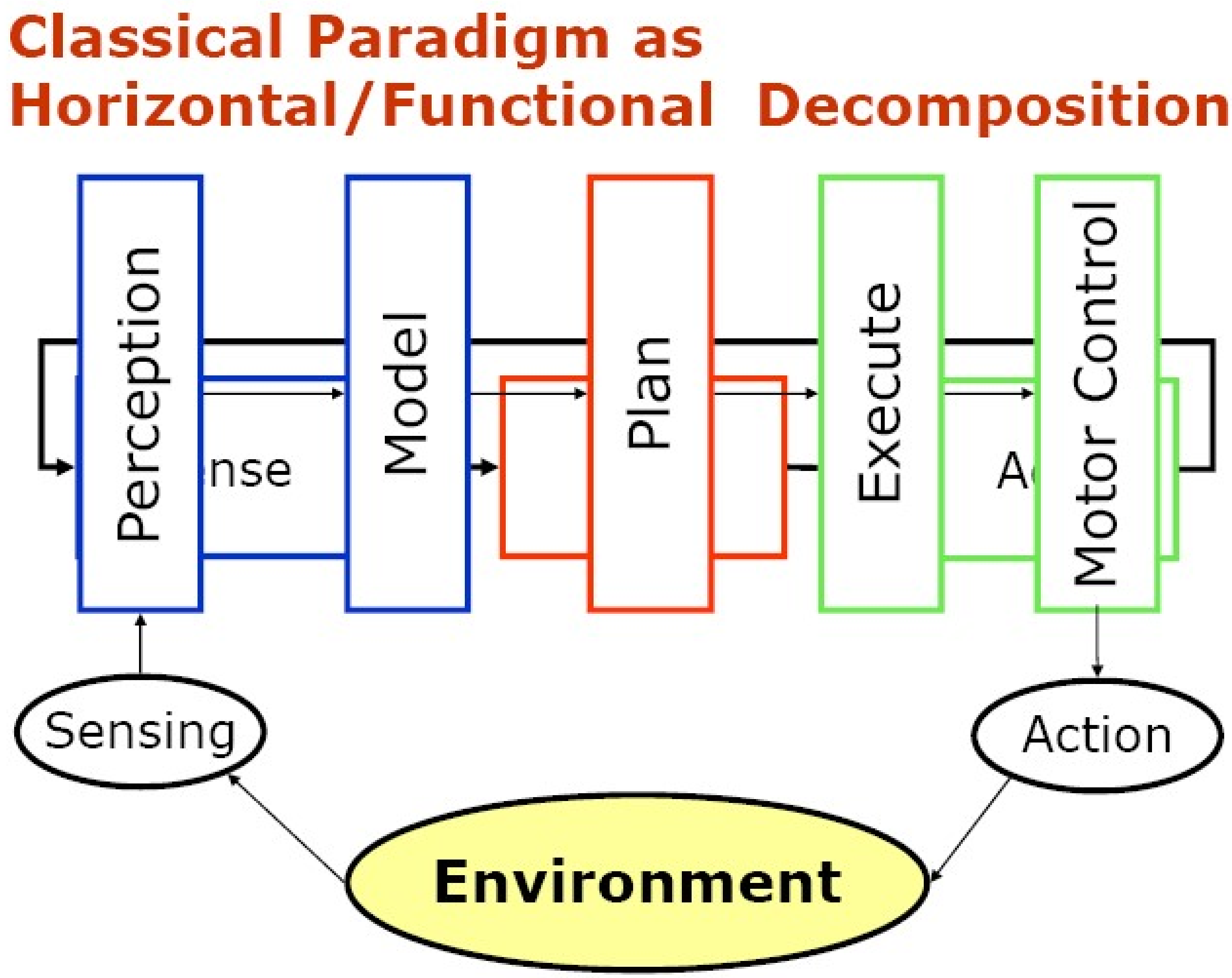


Classical Paradigm

- Hierarchical organization
- Functional decomposition of the activities [Shakey 1969]
- Knowledge Representation and formal reasoning (logic + deductive)
  - Deliberative system
- Environment representation:
  - Deterministic, Symbolic, Observable



Stanford AI Laboratory / CMU (Moravec)
drove the Cart through several 20-m courses (each taking about 5 h)


Classical Paradigm as
Horizontal/Functional Decomposition
Perception
Model
Plan
Execute
Motor Control
Sensing
Action
Environment

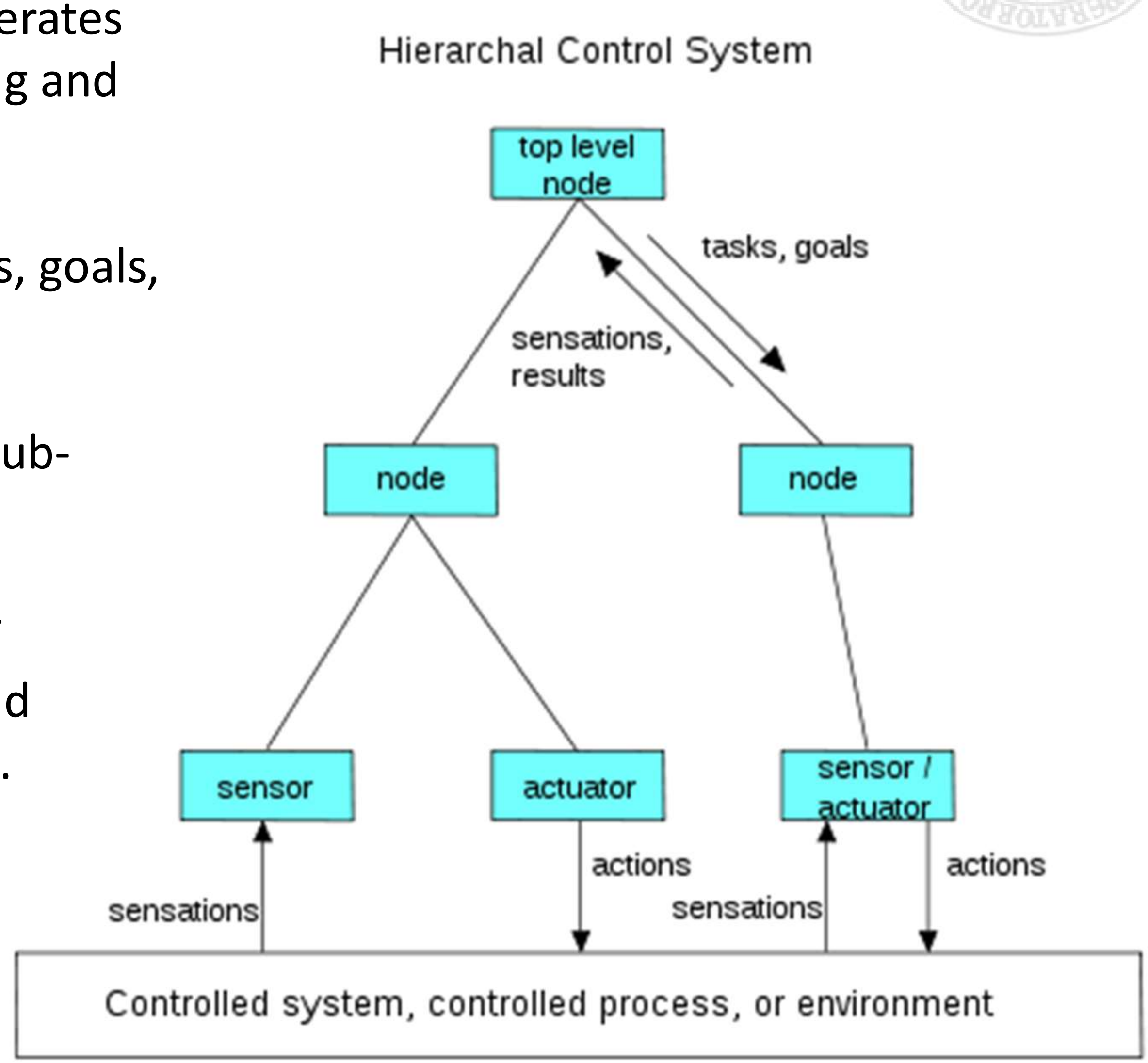
Hierarchical Paradigm

Each higher layer of the tree operates with a longer interval of planning and execution time

The lower layers have local tasks, goals, and sensations

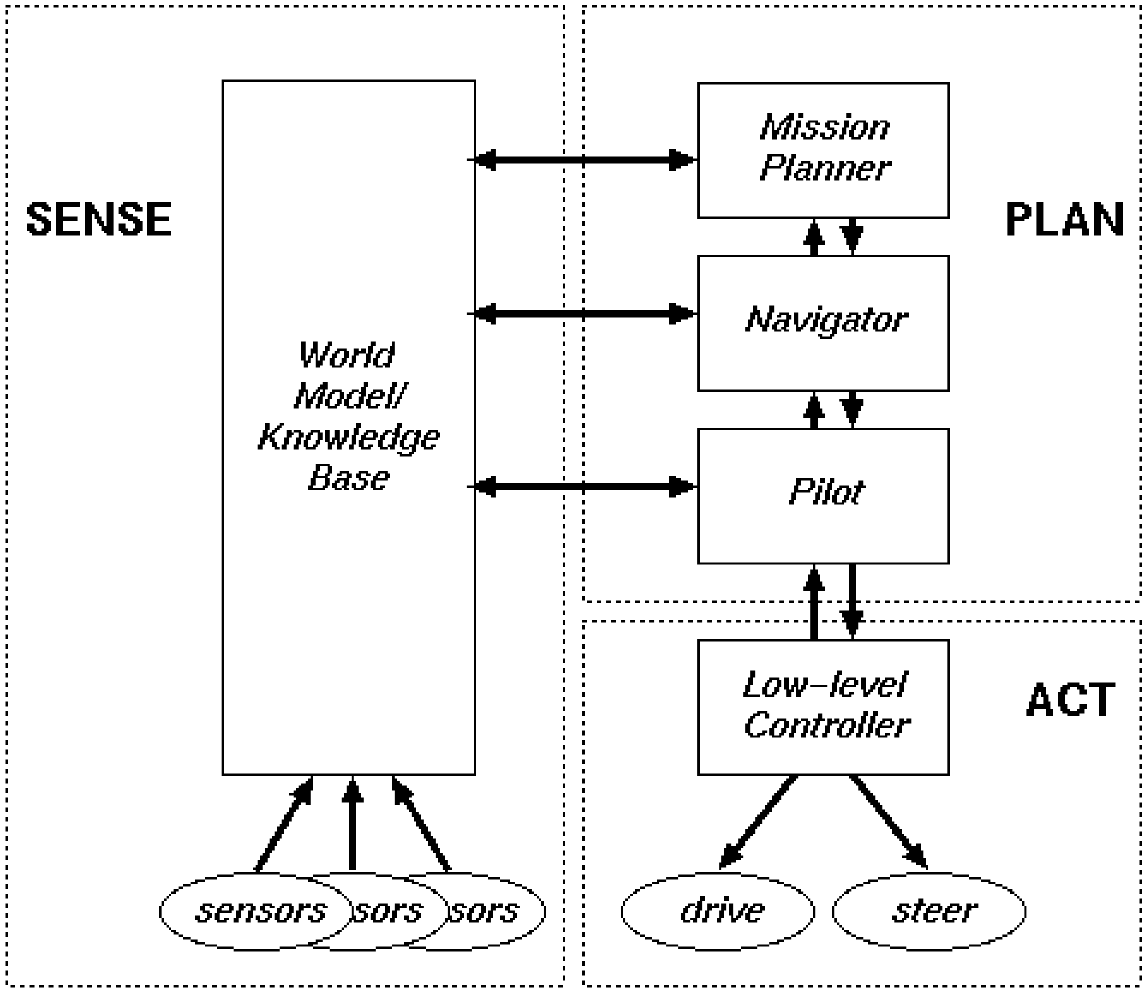
The lowest, reactive layers are sub-symbolic.

The higher layers are capable of reasoning from an abstract world model and performing planning.



Classical Paradigm

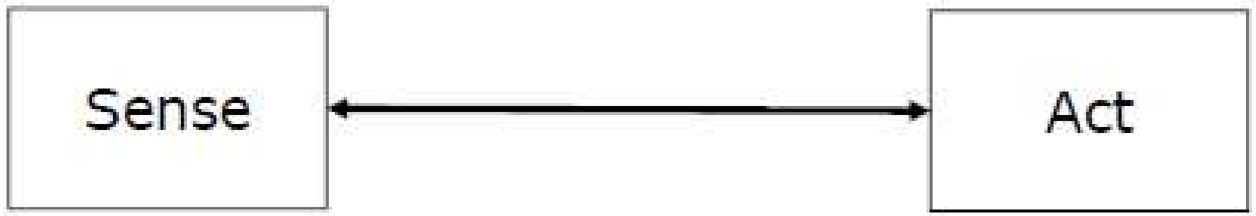
- Nested Hierarchical Controller or NHC (Mystel, 1986)



Disadvantages

- Slow control cycle:
  - Deliberative planning can be very slow
  - Not reactive
- Global representation:
  - “global world” representation that contains the information needed for planning
  - Consistency in a dynamic and uncertain environment
  - Large search space
  - Astraction

Reactive / Behavior-based Paradigm



- No models: The world is its own, best model
- Easy successes, but also limitations
- Investigate biological systems

DIETI

Behavior-based Robotics

- Behavior and body:
  - No model, no reasoning, no planning
    - «Elephants don’t play chess» [Brooks 90]
  - Ethology (bio-inspired)
    - Animal behavior [Tinbergen 51, Lorenz 49]:
    - Environment, behavioral schemata, sensorimotor processes

Pardigm:
Sense
Act

Rodney Brooks

Reactive Paradigm

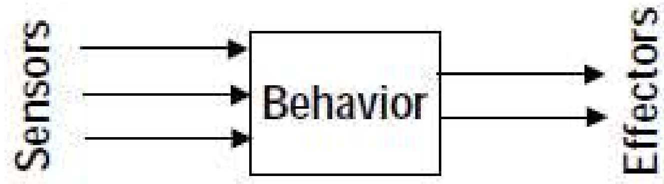
- Ethology: The study of animal behavior in natural conditions

- "Founding fathers" of ethology: Konrad Lorenz and Niko Tinbergen (Nobel prize winners in 1973)
  - They studied:
    - Individual animal behaviors
    - How animals acquire behaviors
    - How animals select or coordinate groups of behaviors

Lorenz

Reactive Paradigm

- Behavior: Mapping of sensory inputs to a pattern of motor actions that are used to achieve a task



- Three broad categories of behaviors:
  - Reflexive behaviors:
    - Stimulus-response
    - Hard-wired for fast response
    - Example: (physical) knee-jerk reaction
  - Reactive behaviors:
    - Learned
    - "Compiled down" to be executed without conscious thought
    - Examples: "muscle memory" – playing piano, riding bicycle, running, etc.
  - Conscious behaviors:
    - Require deliberative thought
    - Examples: writing computer code, completing your tax returns, etc.

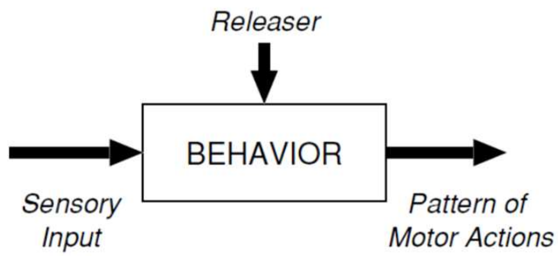
Behaviors

- Reflexive behaviors
  - Reflexes
    - the response lasts only as long as the stimulus
    - The response is proportional to the intensity of the stimulus
  - Taxes
    - the response to stimulus results in a movement towards or away of the stimulus, e.g., moving to light, warm, etc.
  - Fixed-Action Patterns
    - the response continues for a longer duration than the stimulus (fleeing predators)

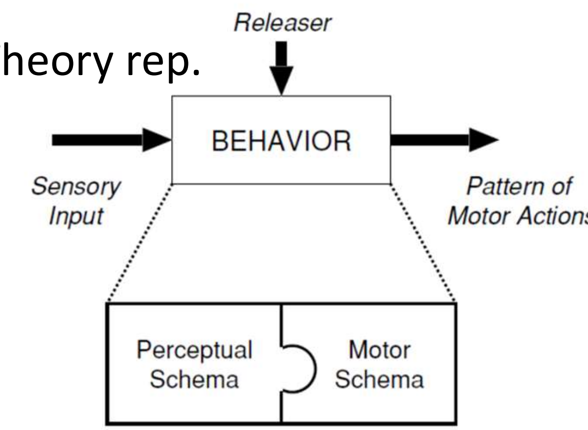
- Coordination and Control of Behaviors
  - Innate behavior
  - Sequence of innate behaviors
  - Innate with memory (bees)
  - Learned behaviors (hunting behaviors)

Behaviors

- Innate releasing mechanisms (Lorenz & Tinbergen)
  - Stimulus and stereotypical pattern of actions



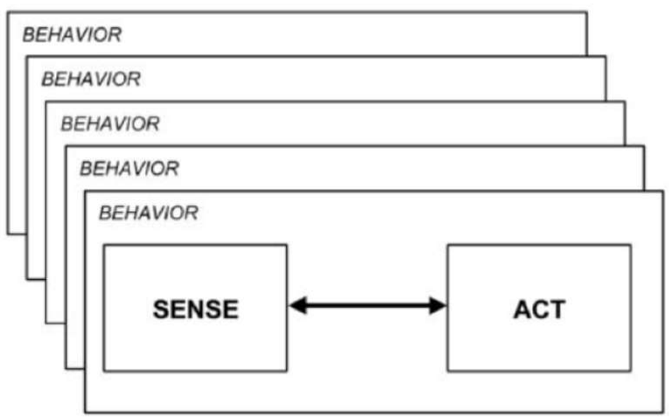
Schema Theory rep.



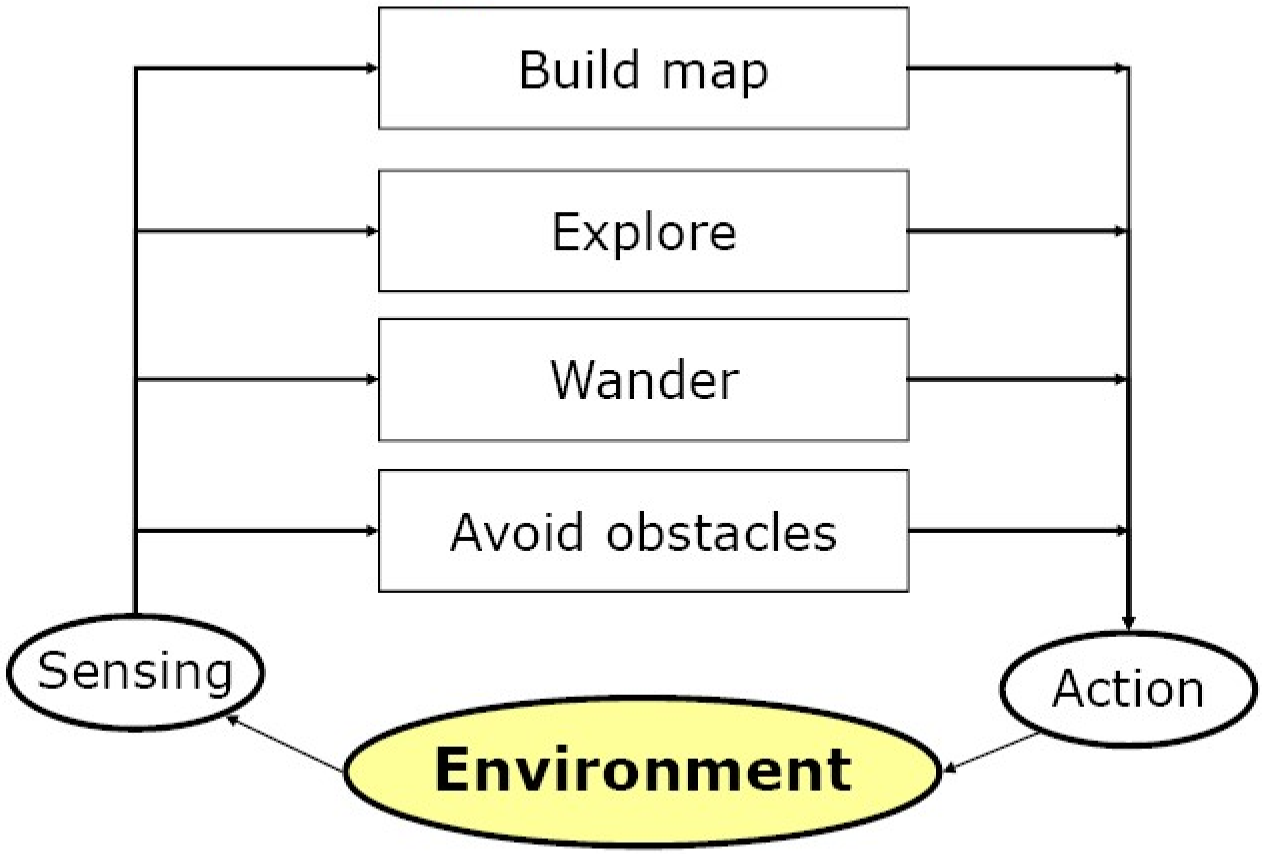
- Concurrent behaviors
  - Behaviors can execute concurrently and independently
    - Equilibrium – the behaviors balance each other
    - Dominance of one – winner takes all as only one behavior can execute and not both simultaneously
    - Cancellation – the behaviors cancel each other out

Robot Behaviors

- Design principles for behavior-based robotics
  - "Programs should decompose complex actions into independent behaviors, which tightly couple sensing and acting. Behaviors are inherently parallel and distributed"
  - "perception should filter sensing and consider only what is relevant to the behavior (action-oriented perception)"
  - "Behaviors are independent, but the output from one may be combined with another to produce a resultant output, or may serve to inhibit another (competing-cooperating)" [Murphy]



Reactive Paradigm as Vertical Decomposition



Characteristics of Reactive Paradigm

- Situated agent, robot is integral part of the world.
- No memory, controlled by what is happening in the world.
- Tight coupling between perception and action via behaviors.
- Only local, behavior-specific sensing is permitted (ego-centric representation).

Behaviors

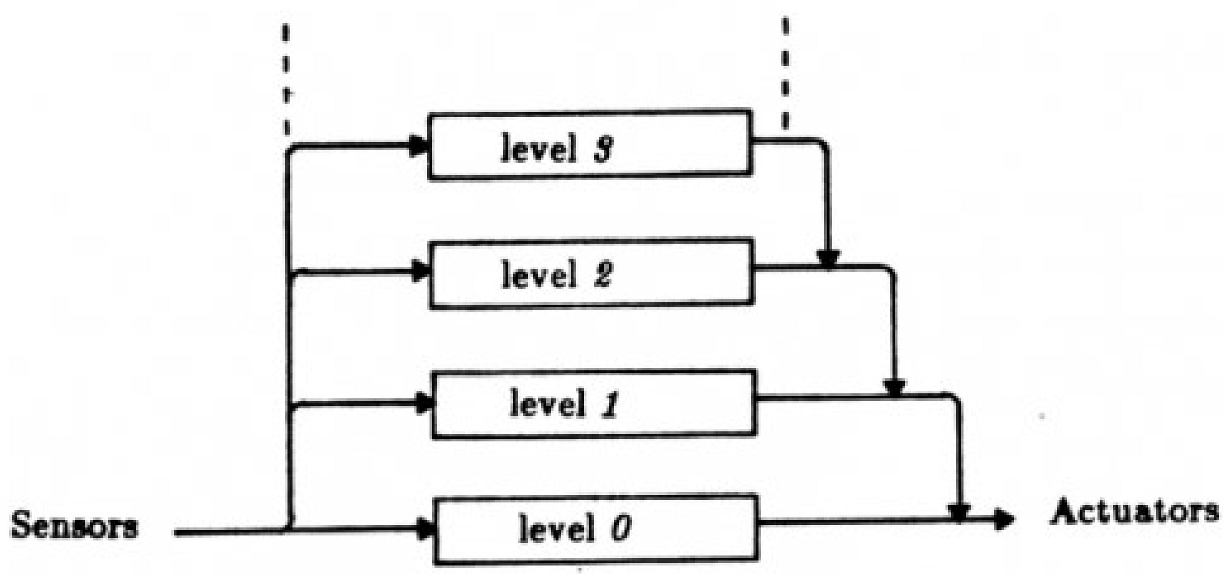
- ... are a direct mapping of sensory inputs to a pattern of motor actions that are then used to achieve a task.
- ... serve as the basic building block for robotics actions, and the overall behavior of the robot is emergent.
- ... support good software design principles due to modularity.

Subsumption Architecture

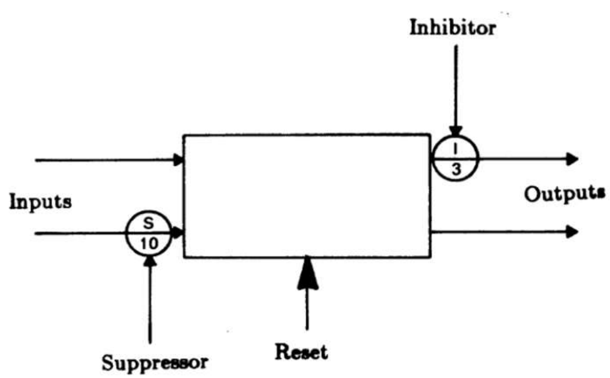
- Introduced by Rodney Brooks '86.
- Behaviors are networks of sensing and acting modules (augmented finite state machines AFSM).
- Modules are grouped into layers of competence.
- Layers can subsume lower layers.
- No internal state!

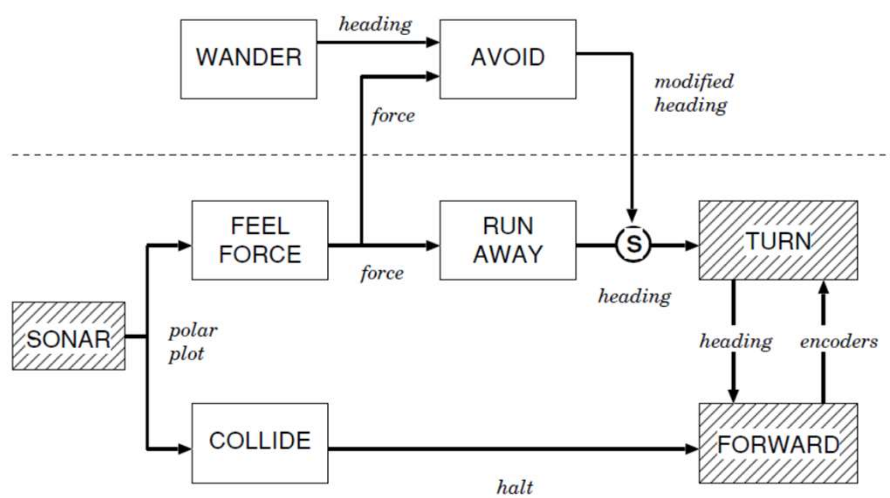
Reactive Paradigm

- Subsumption architecture [Brooks 86]
  - deployed in many robots enabled with basic capabilities (walking, collision avoidance, etc.)
  - Systems are built bottom-up
  - Behaviors are released in a stimulus-response way
  - Components are organized in layers (lowest layers handle most basic tasks)
  - all rules can be executed in parallel
  - newly added components and layers exploit the existing ones



- Subsumption architecture [Brooks 86]
  - Each behavior is represented as an augmented finite state machine (AFSMs)
  - Stimulus (input) or response (output) can be inhibited or suppressed by other active behaviors
  - AFSMs are connected with communication wires, which pass input and output messages between them; only the last message is kept
  - AFSMs run asynchronously





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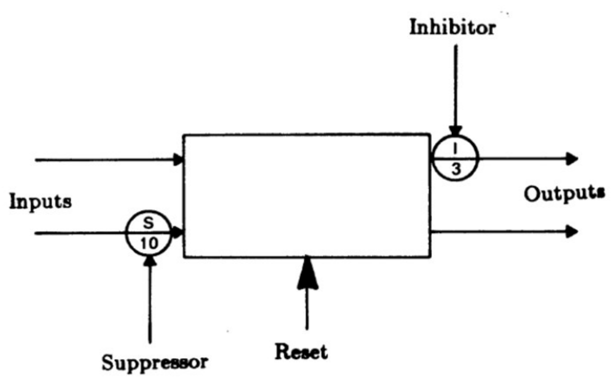
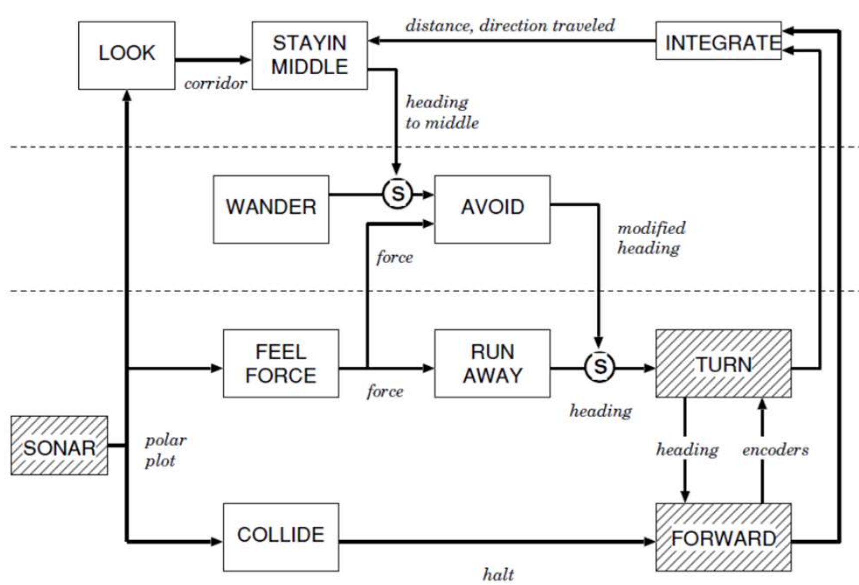


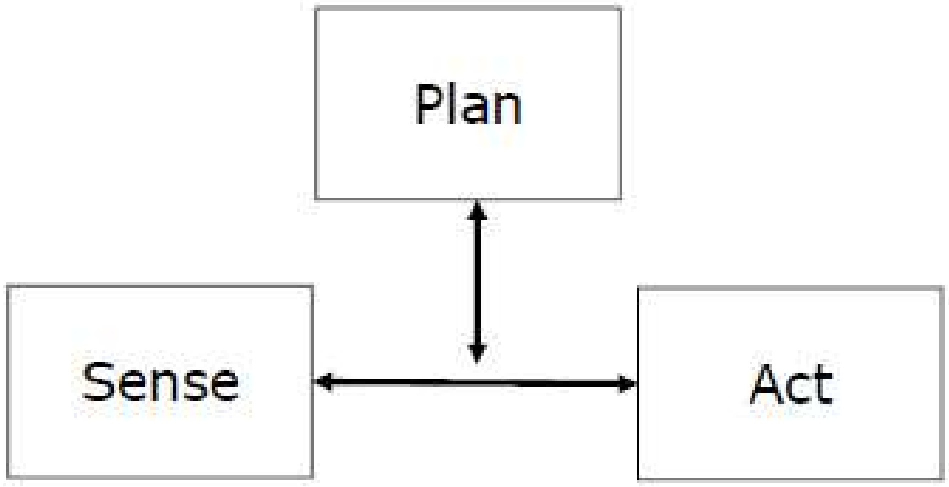


- Subsumption architecture [Brooks 86]
  - No model
  - Use the world as the best model
  - The world can provide the information directly (through sensing) ….
  - …. while an internal representation can be large, slow, expensive, and outdated)

  - Subsumption has been used on a variety of effective implemented robotic systems
  - First architecture demonstrate on real-world working robots

- Subsumption architecture [Brooks 86]
  - On the other hand …
  - No representation
  - No memory
  - No reasoning/problem solving
  - No planning
  - No learning
  - No localization, no mapping
  - Not ease to scale with behavior complexity
  - Not easily taskable

Hybrid Deliberative/reactive Paradigm

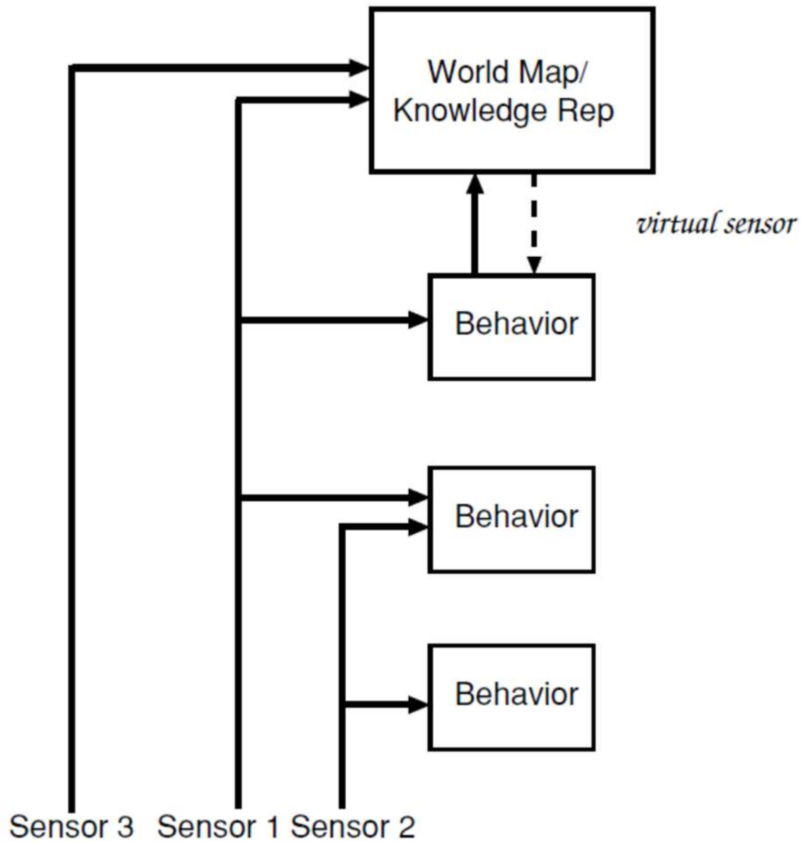


- Combines advantages of previous paradigms
  - World model used for planning
  - Closed loop, reactive control

Hybrid Paradigm

Local and behavior specific sensing as for the Reactive Paradigm.
Planning and deliberation requires global world models.

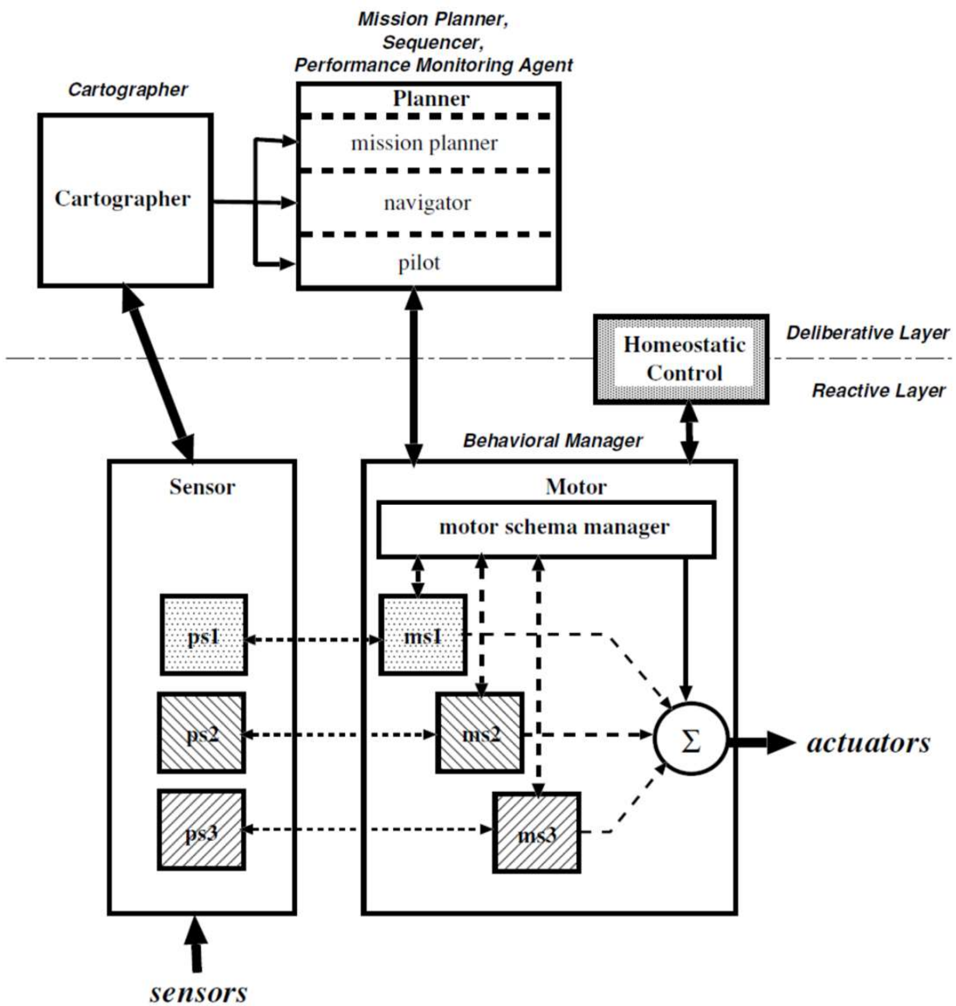
In the Hybrid Paradigm, the term “behavior” includes reflexive, innate, and learned behaviors.



Hybrid Paradigm

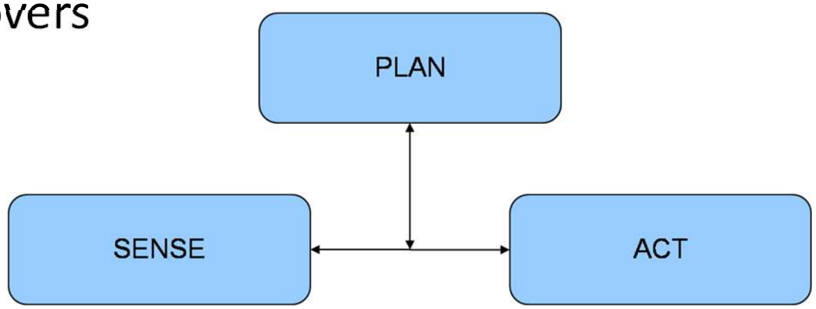
Local and behavior specific sensing as for the Reactive Paradigm.
Planning and deliberation requires global world models.

Autonomous Robot Architecture (AuRA) [Brooks 1988]



Hybrid Paradigm

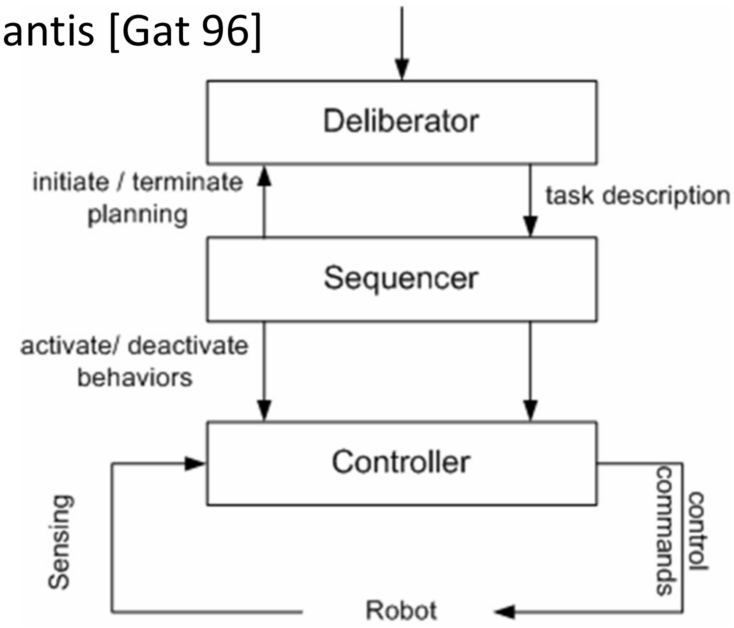
- 3T architectures [Gat 1996, Bonasso et. al 1998] predominately used at NASA for planetary rovers and robot assistants



  - Model-based planning and reasoning
  - Reactive at the low-level control

    - Deliberative Layer
    - Sequencing Layer
    - Skill Layer

Atlantis [Gat 96]

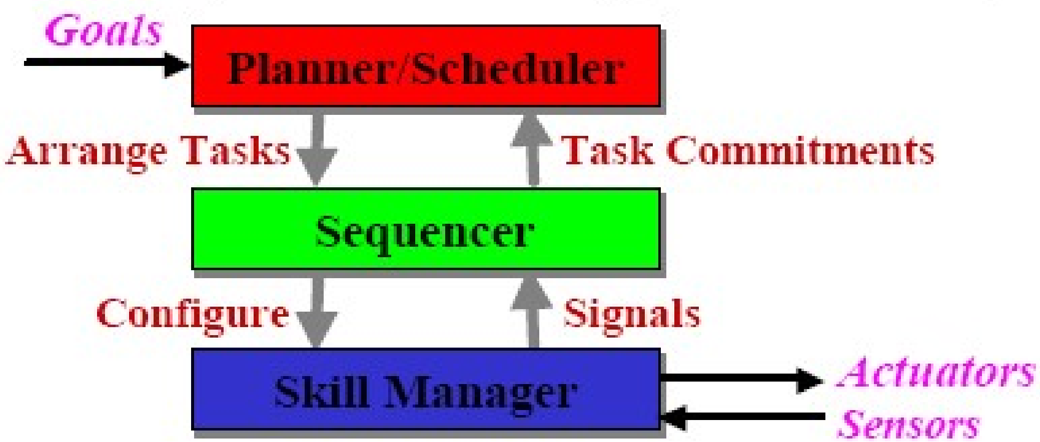


3 Layered Architectures

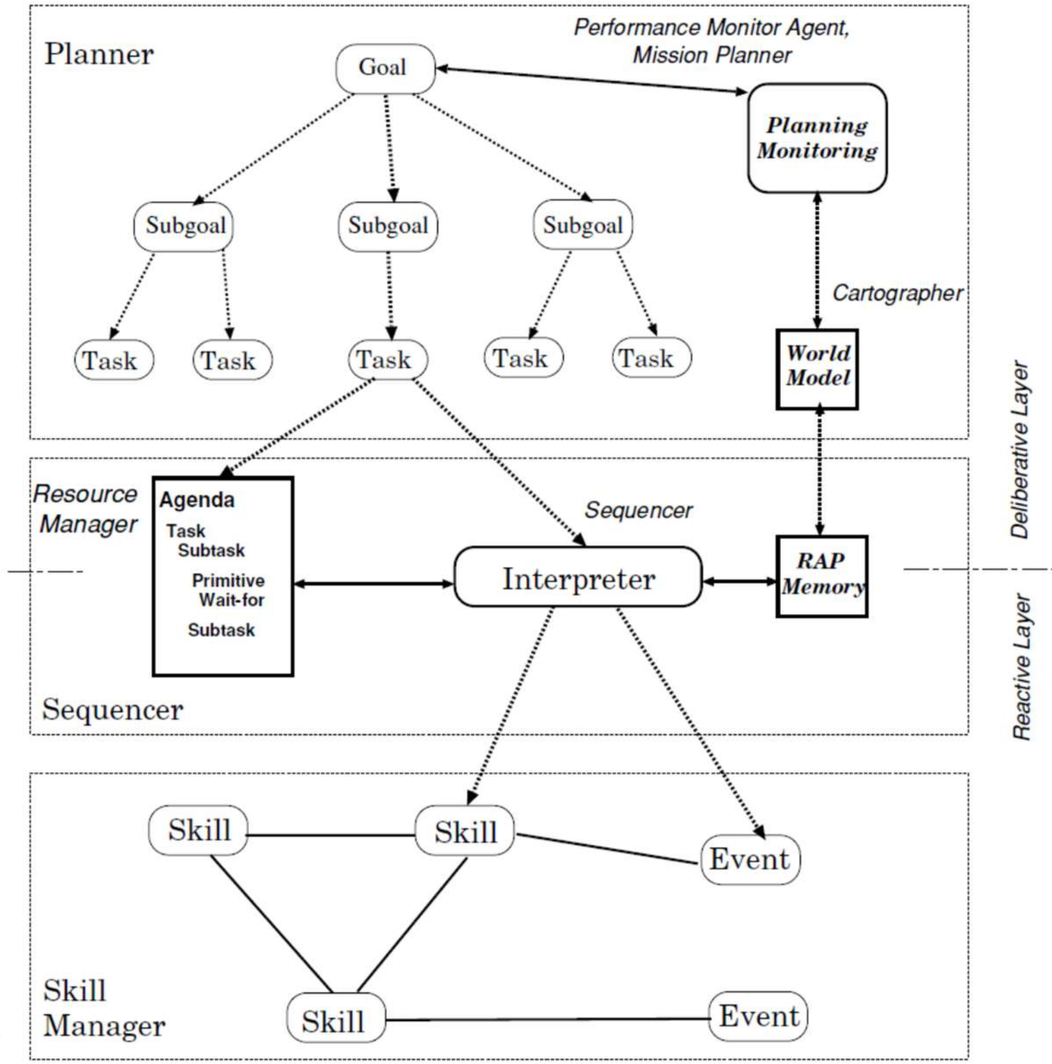
- Deliberative layer:
  Plan, reasoning, deliberation
- Executive layer:
  execution monitoring, scheduling, sequencing, dispatching, recovery, synchronization, etc.
- Functional layer:
  specialized controllers, perceptive systems, sensory-motor loops, reactive behaviors

3T Architecture: ATLANTIS

- Explicit Separation of Planning, Sequencing, and Control
  - Upper layers provide *control flow* for lower layers
  - Lower layers provide *status* (state change) and *synchronization* (success/failure) for upper layers
- Heterogeneous Architecture
  - Each layer utilizes algorithms tuned for its particular role
  - Each layer has a representation to support its reasoning



Reactive Action Packages (RAPs) [Firby 1989]



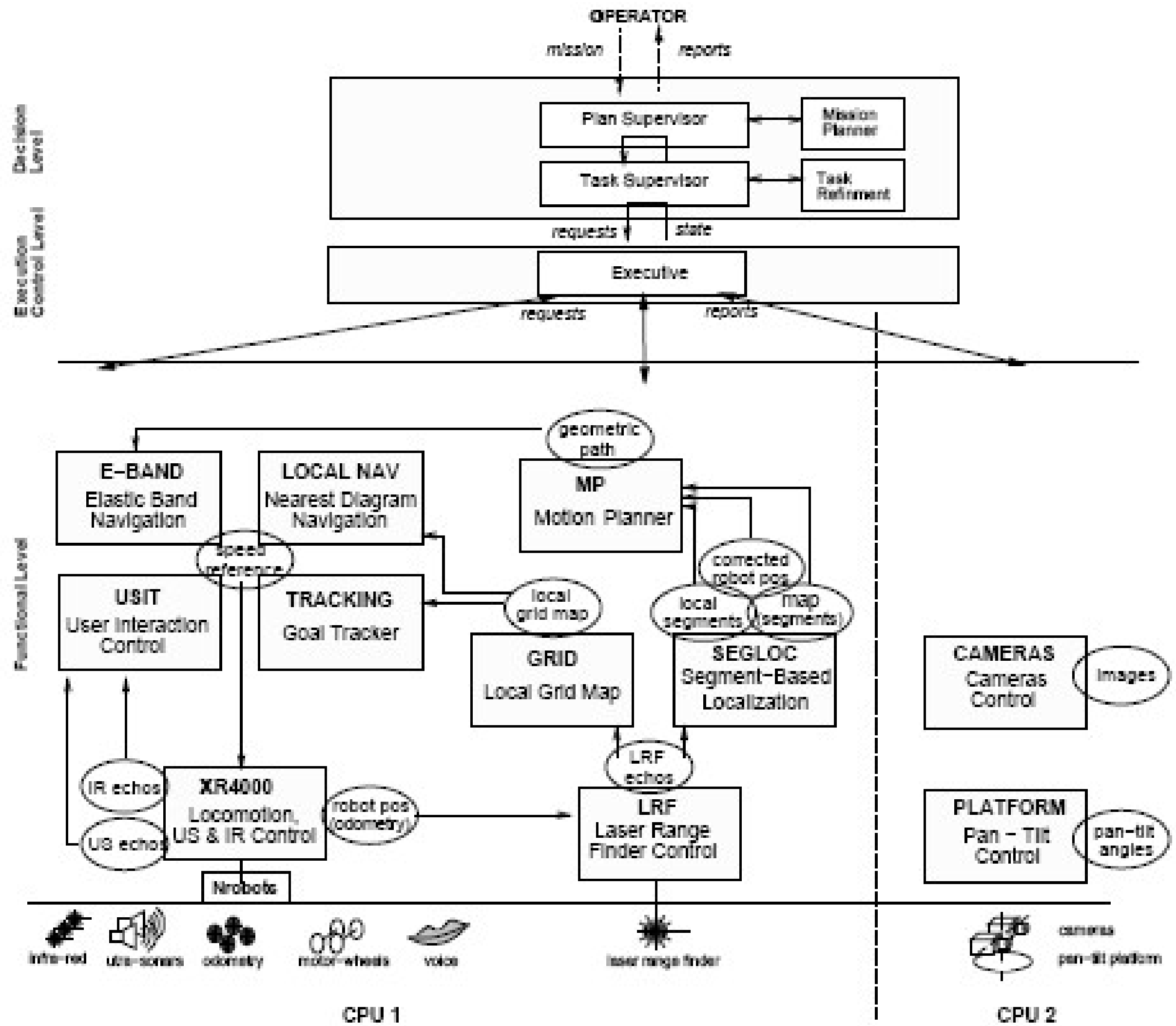
3T Architecture

- LAAS architecture:

Three Layers:

1. Deliberative (temporal planner)
2. Executive (PRS)
3. Functional (GENOME)

Rover Control

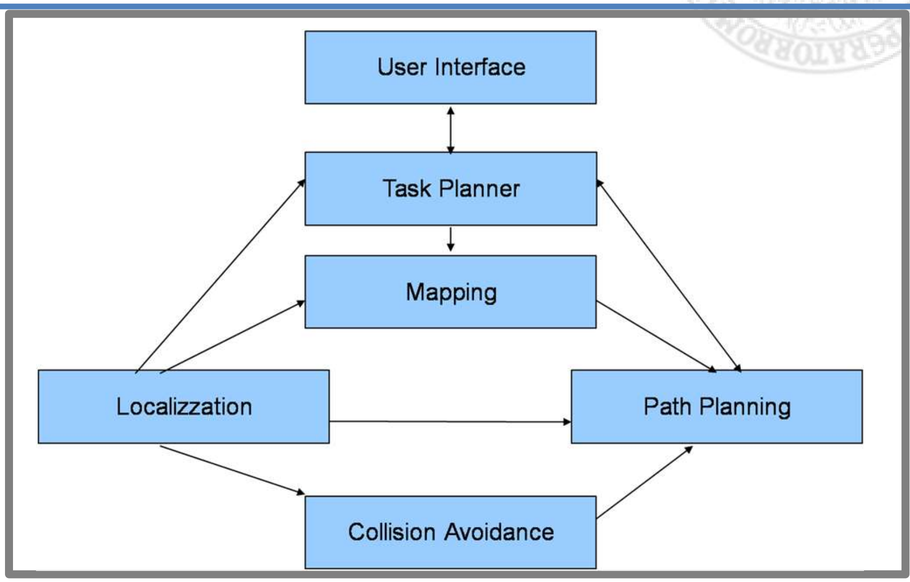


RHINO Architecture

Robotic tour guide - Bonn Science museum (1995); MINERVA – Atlanta (1998)

3T mobile robot:

1. Functional:
   Mapping, Localizzation, Obstacle Avoidance
2. Executive:
   Sequencer, monitor
3. Deliberative:
   Task Planner (tour planner)



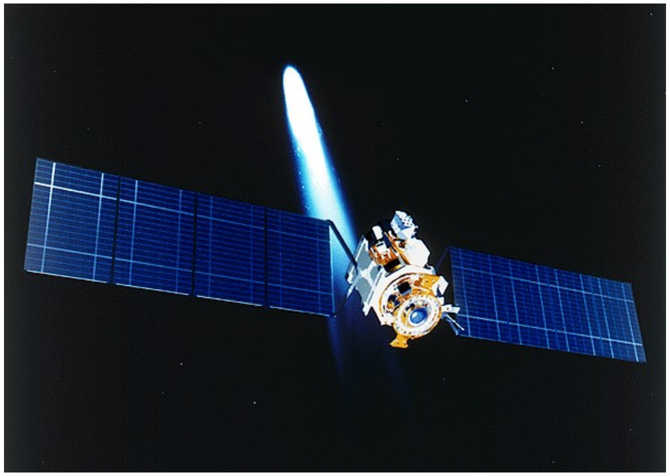
RHINO Architetture

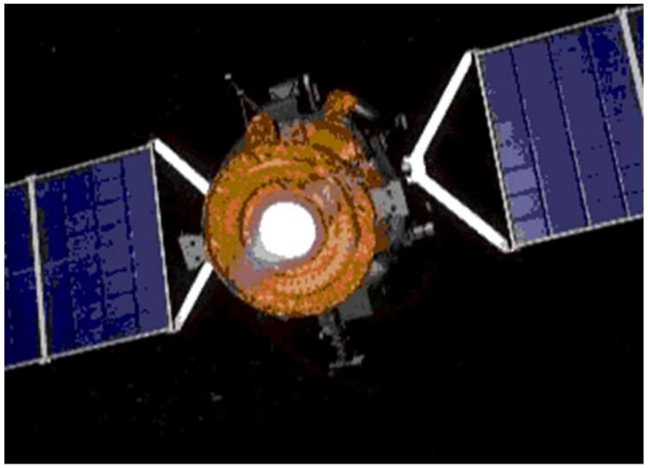
Rhino, 1997

Minerva, 1998

DS1 (Remote Agent)

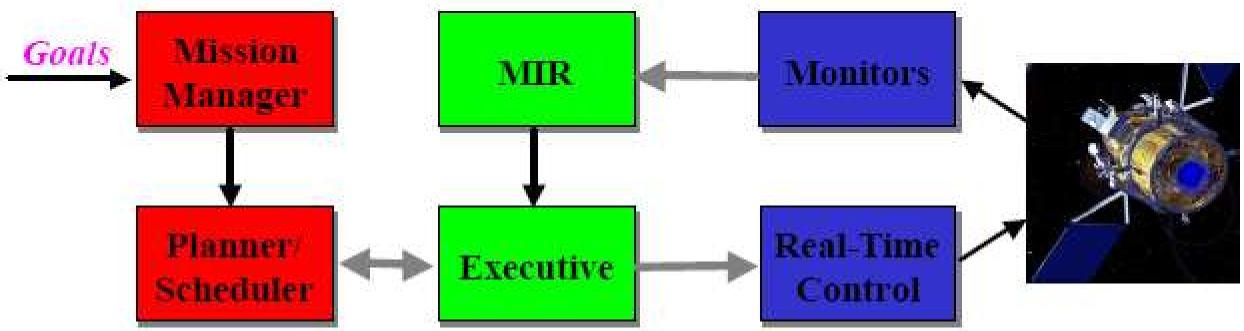
- Mission: testing new technologies for the New Millennium Program (and observe Borrelly comet)
- First autonomous spacecraft
- Planner and smart executive system (RAX: Remote Agent Experiment).
- Planning, scheduling, adaptive execution, diagnosis, recovery.



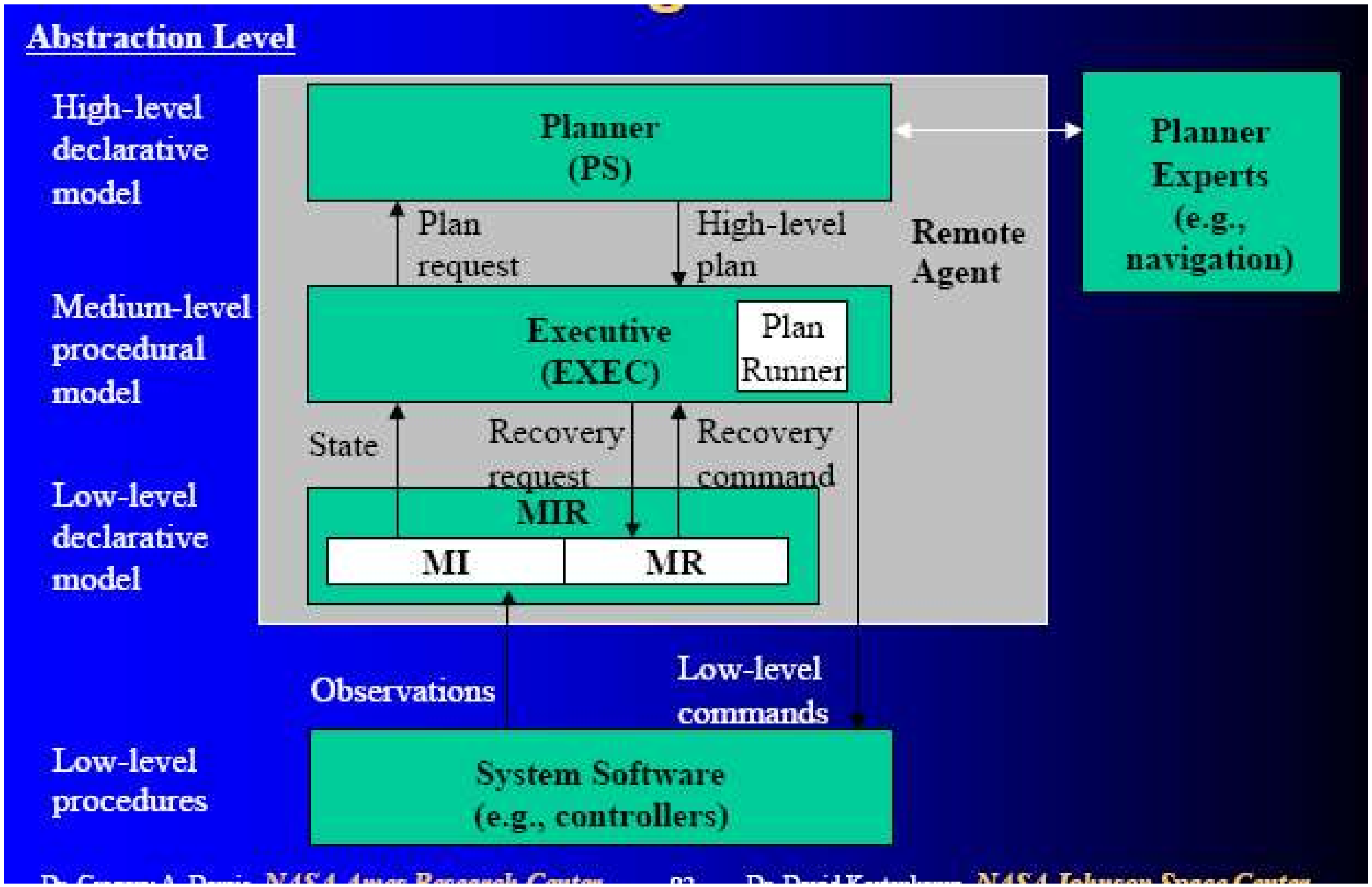


3T: REX

- Remote Agent:
  - Three Layers:
    - Mission Manager, Temporal planning and scheduling
    - Execution Monitoring/Dispatching, Mode Identification (Diagnosis) and Recovery (MIR)
    - Reflex control, sense (real-time)



3T: REX



Abstraction Level
High-level declarative model
Medium-level procedural model
Low-level declarative model
Low-level procedures
Planner (PS)
Plan request
High-level plan
Remote Agent
Planner Experts (e.g., navigation)
Executive (EXEC)
Plan Runner
State
Recovery request
Recovery command
MIR
MI
MR
Observations
Low-level commands
System Software (e.g., controllers)

3T Architectures

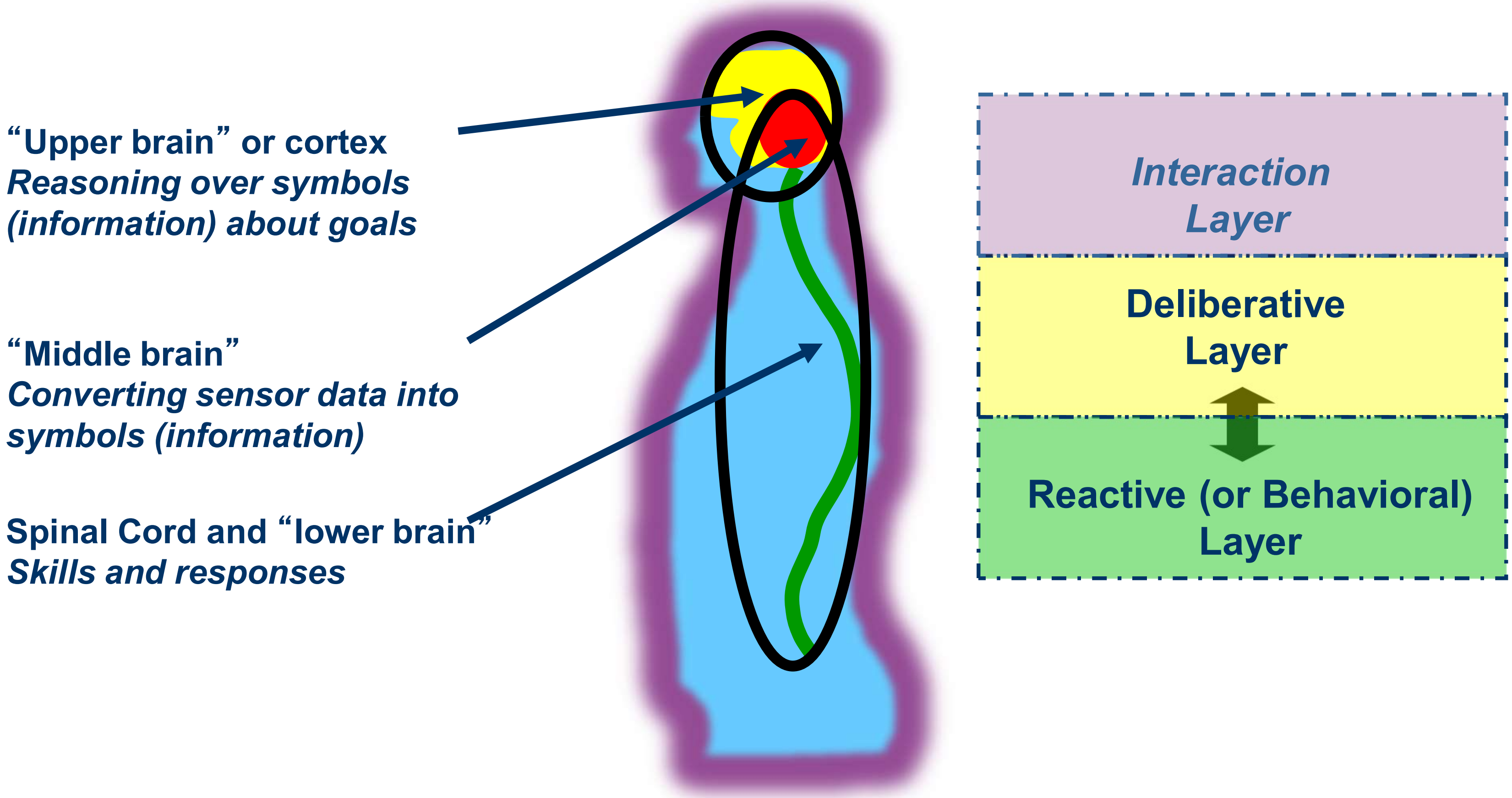
Problems with 3T:
Modular architectures but …

- Heterogeneous (different models)
- Abstraction level == control level:
  - HL abstract deliberation (task and mission planning)
  - LL reaction (implicit model, no flexible)
- Interaction deliberative-reactive?
  - Plan-Exec interaction
  - Replanning
  - Several exec-monitor-control loops
- Ad hoc executive system (when too complex, only sequencer and dispatcher)

Executive Layer: the key stone

- Forms a Bridge Between Planning and Behaviors
  - Discrete vs. continuous control
  - Symbolic vs. numeric representations
  - Real-time considerations
- Basic Roles
  - Decompose task into subtasks and dispatch tasks
  - Monitor execution for contingencies and opportunities
  - Reschedule tasks (or schedule new tasks) upon failure
- Differences Between Approaches
  - Methods for distributing functionality
  - Representation of domain and control knowledge
  - **RAP** (Firby); **TCA/TDL** (Simmons); ESL (Gat); PRS (Georgeoff)

Biological Metaphor*



*An amazingly sweeping generalization for the purpose of metaphor

Cognitive Architectures

- Field Robotics : Autonomous robot, adaptive and flexible behavior
- Social Robotics : Interaction, Interpretation, Lifelong learning

Robotic Architetture as Cognitive Architectures:

Additional capabilities:
- Sensor fusion
- Reasoning
- Deliberation
- Learning

- Perception/Recognition and Perception/Action
- Attention and Executive Control
- Sensory-motor coordination (synergies)
- Motivations, emotions
- Human-robot interaction
- Incremental Learning (developmental robotics)

Cognitive Architectures: ACT-R (1993)

Cognitive Plausability:
Testing cognition theories

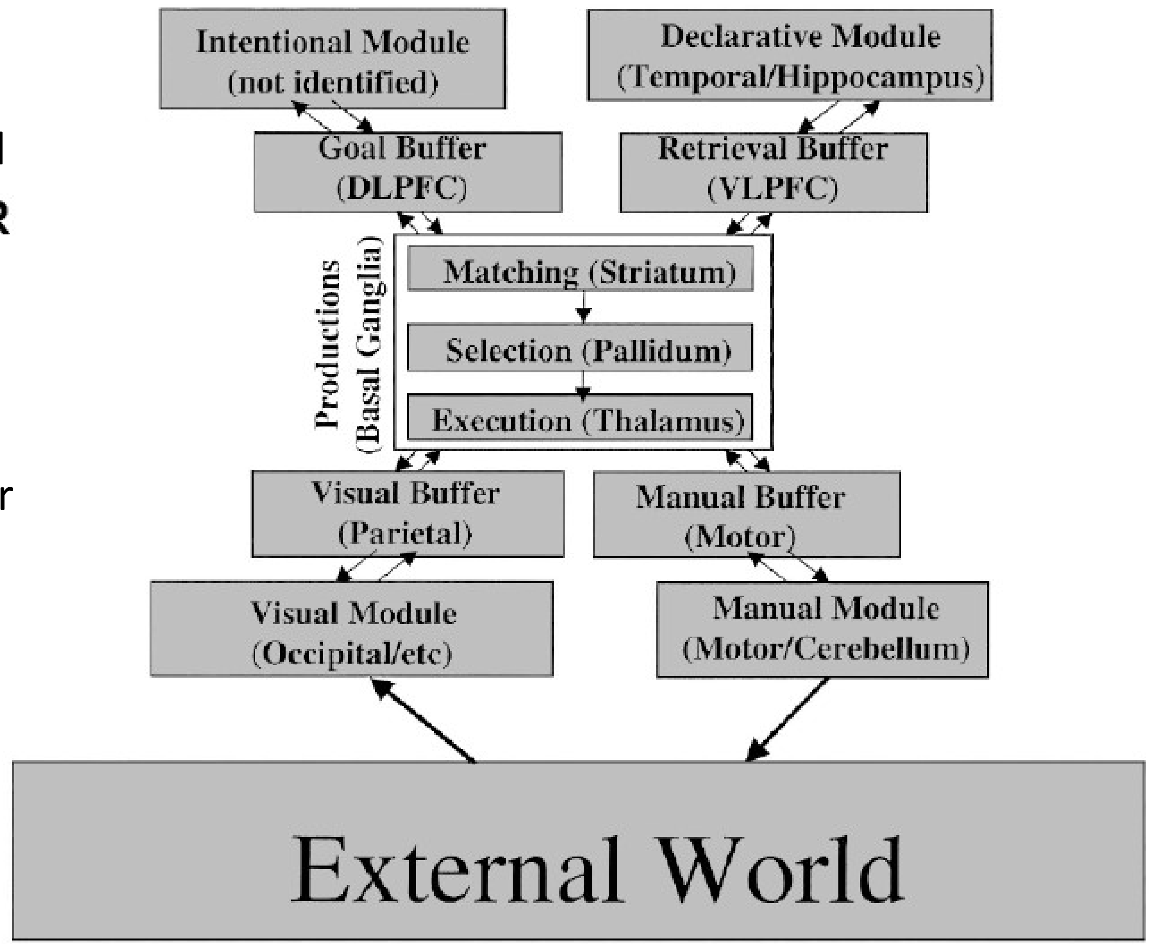
Embodied Agent: used to control robots

Two memories: procedural and associative

The pattern matcher searches for a production that matches the current state of the buffers

ACT-R cognition as a succession of production firings.

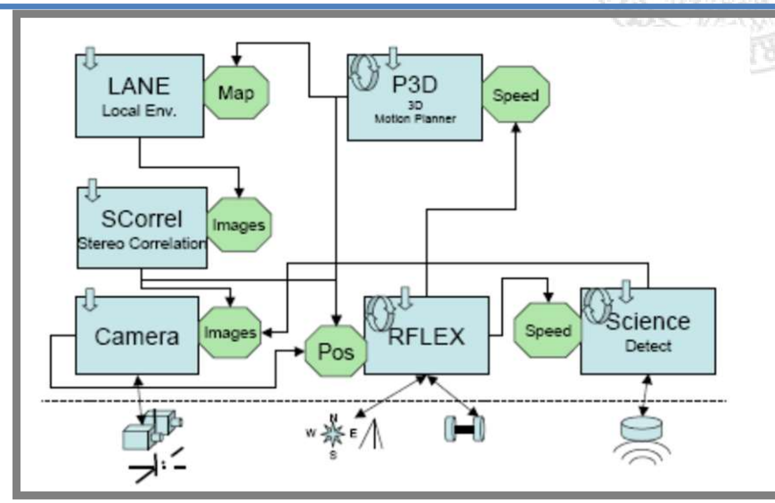
ACT-R



Functional

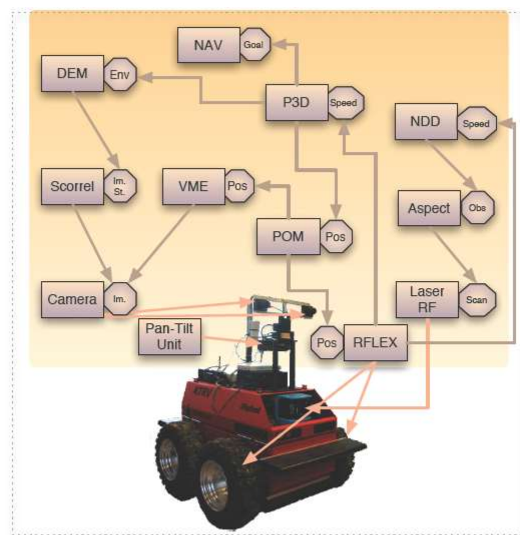
Functionalities:

- Avoidance
- Mapping
- Localization
- Navigation
- Perception/recognition object,situation,place,...
- Object manipulation
- Visual perception
- Human-robot interaction
- ...



Esempio: GENOME functional layer

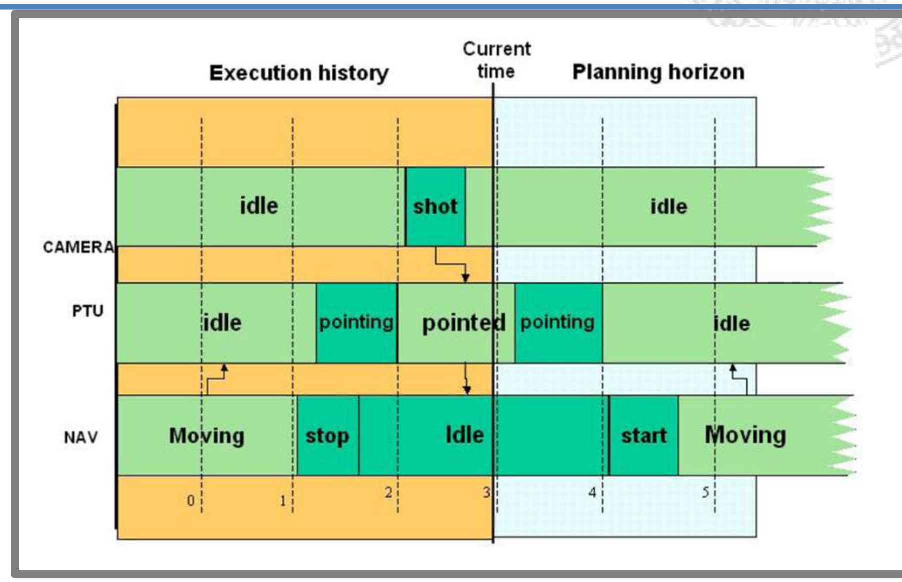
Livello funzionale in



Deliberative layer

Planning and Decision Making:

- Task planning
- Reactive/Dynamic Planning
- Path Planning
- Temporal, dynamic reasoning,etc.
- Decision Making



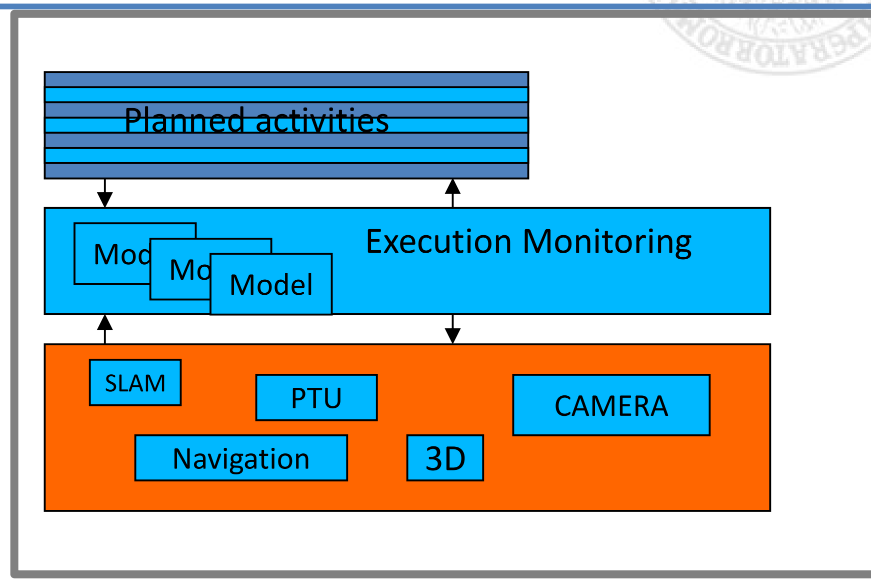
Example: Timeline-based Planning

- Environment models (maps, constraints, cause-effects, dynamics, etc.)
- Robot Models (sensor/actuator)
- Decision Models (utility, costs etc.)
- Interaction Models (HRI)

Executive Layer

Between functional and deliberative:

- Sensory-motor coordination
- Deliberative-reactive coordination
- Execution monitoring
- Error detection, diagnosis and recover
- Adapt/Rapair/Replanning

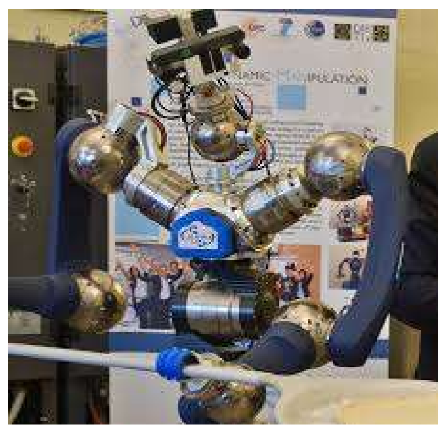


Issues

- Functional, Deliberative and Executive layers:
  - Functional layer:
    - Mobile robotics and probabilistic robotics (mapping e localizzation, navigation, exploration, etc.)
    - Bayesian models, bayesian filters
  - Executive layer:
    - Execution monitoring and dynamic planning; cognitive control and attentional systems
    - Temporal models, automata, cognitive models, etc.
  - Deliberative layer:
    - Planning and scheduling; planning and execution; decision theoric planning; reinforcement learning
    - Temporal models, markov models, etc..

Tools

- Laboratorio PRISMA
- Centro ICAROS



DIETI

Software

- Strumenti software