Robotics Modelling Approaches to Cognitive Sciences

Introduction + Course 1
Neuro-/Developmental- Robotics
Mehdi Khamassi
CA10 Cogmaster, March. 2019

Acknowledgments: With the input of Nicolas Bredèche, Raja Chatila, Stéphane Doncieux & Benoît Girard.
Course Objectives

• To understand in which manners current researches in Robotics can contribute to Cognitive Sciences.

• Some similar questions with a robot than those raised about biological organisms.

• Source of computational solutions that work in the real-world (not only in simulation).

• Testbed of biological and psychological hypotheses.

• Robotics can raise new questions to be later addressed in Biology or Psychology.
Inter-disciplinarity

Artificial Intelligence

Ethology / Sociology

Human and Social Sciences

Robotic modelling approaches to Cognitive Sciences

Computational Neuroscience

Developmental Psychology

Signal processing

Engineering Fields

Cognitive Robotics

Robotics (Mechatronics)

Biology
Course Organization

14 sessions (+ 4 labs - Durkheim)

1. Introduction (Chatila/Khamassi)  
   5 Mar - de Brogli E
2. Active Perception (Gas)  
   12 Mar - de Brogli E
3. (Deep) Reinfor. Learning (Sigaud)  
   19 Mar - de Brogli E
4. RL and off-line replay (Khamassi)  
   26 Mar – de Brogli E
5. Deep learning (Ollion)  
   2 Apr - de Brogli E
6. Language (Dominey)  
   9 Apr - de Brogli E
7. Development (Oudeyer)  
   16 Apr – de Brogli E
8. Spatial Cognition (Arleo)  
   22 Apr – de Brogli E
   29 Apr – de Brogli E
10. Bayesian Approaches (Bessière)  
    13 May - de Brogli E
11. Social signals (Chetouani/Gaussier)  
    20 May - de Brogli E
12. Motor control (Guigon)  
    28 May - de Brogli E
13. Evolution Rob (Bredèche/Doncieux)  
    4 Jun - de Brogli E
14. Final Evaluation  
    11 Jun - de Brogli E
Course Organization

What is the best date and time for the 4 labs?
Course validation

• 4 grades obtained during the labs  
  (50% of total score)
• 1 grade during final validation: oral  
  presentation of the synthesis+replication of a  
  computational research article  
  (50% total score)
• Soon: List of proposed articles.
Today: course #1

Raja Chatila
• Introduction to Cognitive Robotics
• Towards robotic cognitive architectures

Mehdi Khamassi
• Intro to Neuro-/Developmental- Robotics

• Two different approaches but the same awareness of the importance of the body and of sensori-motor processes in cognition.
Today: course #1

Raja Chatila
• Introduction to Cognitive Robotics
• Towards robotic cognitive architectures

Mehdi Khamassi
• Intro to Cognitive Robotics
• Intro to Neuro-/Developmental- Robotics
• Towards robotic cognitive architectures
• Different approaches but shared importance of the body/sensori-motor processes in cognition.
Important characteristics of cognitive robots...

• **They are physical entities** (need to take into account: time, energy, body-environment interactions).

• **They act in the real-world** (facing situations that had not been predicted by the researcher).

• **They need to perceive, analyze, act** (requires an integration between cognitive functions and hypotheses about their interaction).

• **They learn incrementally** (need for a developmental process and a motivation to explore/learn)

• **They need to adapt/generalize to different application domains** (need for a cognitive architecture).
...which make them different from (but complementary to)

• Initial Symbolic Artificial Intelligence (only interested in high-level reasoning without taking sensory-motor processes into account).

• Industrial Robot (pre-programmed to solve the same pre-specified task).

• Computational Neuroscience Models (which work in perfectly controlled simulations).
Different approaches

• Engineering
• Bio-inspired
• Bio-mimetic
• Symbolic
• Emergent
• Connexionnist
• Bayesian
• ...
Different levels

- Biological/Psychological hypothesis
- Mathematical formalization
- « Perfect » simple discrete simulation (e.g. Matlab)
- « Noisy » simple discrete simulation (e.g. Matlab)
- Continuous synchronous simulation (e.g. Webot)
- Continuous asynchronous simulation (e.g. ROS)
- Robotic experiment (pre-conceived real-world task)
- Robotic generalization (other real-world tasks)
Towards « Intelligent » Robots?

• Can we conceive an « intelligent » robot, able to reason and to think rationally like a human-being?

• But, what is « intelligence »?
Towards « Intelligent » Robots?

• Can we conceive an « intelligent » robot, able to reason and to think rationally like a human-being?
• But, what is « intelligence »?
  – « Turing Test » (1950)
Towards « Intelligent » Robots?

• Can we conceive an « intelligent » robot, able to reason and to think rationally like a human-being?

• But, what is « intelligence »?
  – « Turing Test » (1950)

• Specific cognitive functions preferred: Decisional autonomy, adaptivity, generalization, reasoning, language, motor adaptation, perception, ...
Towards « Intelligent » Robots?

• Some continue to aim at creating a fully « intelligent » robot. Ethical/Societal issues. (Approach not further developed here)
Towards « Intelligent » Robots?

• Some continue to aim at creating a fully « intelligent » robot. Ethical/Societal issues. (Approach not further developed here)

• Focus on the conception of robots in the aim of better understanding humans. Richard Feynman (Physicist): « What I cannot create, I do not understand ». This leads to 2 distinct current objectives.
Two main (sometimes orthogonal) objectives of the presented material
What about Deep learning?

• Have deep learning methods the potential to lead to new success stories?
What about Deep learning?

Yamins DiCarlo 2016

Nat Neurosci

Operations in linear-nonlinear layer

Filter

Threshold

Pool

Normalize

Spatial convolution over image input

Pixels

100-ms visual presentation
Reconstruction of neocortical circuitry
~31,000 neurons ~8 million connections
~37 million synapses

Behavioral & Cognitive Neuroscience
100-500 trials

Niv et al. 2006

Mouret 2016
ERCIM NEWS, Special Issue on Machine Learning

Markram et al. 2015
Main cognitive capabilities of a robot

Slide by Raja Chatila

Perceiving/representing/
Learning space/situations/humans
Main cognitive capabilities of a robot

Slide by Raja Chatila
Main cognitive capabilities of a robot

Slide by Raja Chatila

Perceiving/representing/ Learning space/situations/ humans

Displacing, acting: The movement

Anticipating Deciding Reacting
Main cognitive capabilities of a robot

Slide by Raja Chatila

- Perceiving/representing/Learning space/situations/humans
- Displacing, acting: The movement
- Communicating Interacting
- Anticipating Deciding Reacting
Main cognitive capabilities of a robot
Slide by Raja Chatila

- Perceiving/representing/Learning space/situations/humans
- Learning new capacities
- Communicating/Interacting
- Displacing, acting: The movement
- Anticipating/Deciding/Reacting
Perception is imprecise and uncertain

Slide by Raja Chatila
Integration of allo/idiothetic info

Arleo (2001)
See course by Angelo Arleo
Questions

Slide by Raja Chatila

• How can a robot coherently represent its environment and how can it localize within it?
• How can it plan its own movement, while remaining reactive to changes of the environment?
• How can it make decisions, elaborate action plans, in particular in uncertain and partially unknown environments?
• How can it interact with other agents or humans?
• How can it learn to improve its actions?
• Finally, how can all these functions be organized/integrated within a global cognitive architecture permitting a coherent behavior?
Simultaneous Localization and Mapping (SLAM)
Simultaneous Localization and Mapping (SLAM)

Slide by Raja Chatila
Outils fondamentaux : le filtre Bayésien

Vraisemblance de la mesure \( z_t \)

Priori: Distribution de probabilité de \( x_t \) si le robot était à \( x_{t-1} \) et qu’il a effectué l’action \( u_{t-1} \)

Posteriori si robot à \( x_t \)

\[
p(x_t | z_{1...t}, u_{1...t}) = \eta \, p(z_t | x_t) \int p(x_t | u_t, x_{t-1}) \, p(x_{t-1} | z_{1...t-1}, u_{1...t-1}) \, dx_{t-1}
\]

\( x = \) état: robot + éléments de l’environnement (amers)
\( t = \) temps, \( (k: \) instants discrets)
\( z = \) mesure
\( u = \) commande
\( \eta = \) normalisation

Distribution de probabilité de \( x_{t-1} \)

(itération précédente)

Kalman
Particulaire
Markov
Outils fondamental : le filtre Bayésien

Slide by Raja Chatila

Vraisemblance de la mesure $z_t$ si robot à $x_t$

Priori: Distribution de probabilité de $x_t$ si le robot était à $x_{t-1}$ et qu’il a effectué l’action $u_{t-1}$

Posteriori

\[
p(x_t | z_{1...t}, u_{1...t}) = \eta p(z_t | x_t) \int p(x_t | u_t, x_{t-1}) p(x_{t-1} | z_{1...t-1}, u_{1...t-1}) \, dx_{t-1}
\]

Distribution de probabilité de $x_{t-1}$ (itération précédente)

Cf. Cours de Pierre Bessière

$x = \text{état: robot + éléments de l’environnement (amers)}$
$t = \text{temps, (}k:\text{ instants discrets)}$
$z = \text{mesure}$
$u = \text{commande}$
$\eta = \text{normalisation}$

Kalman
Particulaire
Markov
Interaction et coopération

Evaluation de la situation
Coopération

Multi-modal Dialog
Mutual Activity Observation

Hello!

La perspective de l’autre

Slide by Raja Chatila
Interaction et coopération

Evaluation de la situation
Coopération

Cf. Cours de Chetouani/Gaussier

Multi-modal Dialog
Mutual Activity Observation

Hello!

La perspective de l’autre

Slide by Raja Chatila
CA10 Course 1

- History of Computer/Al/Cybernetics/Robotics
- Introduction to the diversity of approaches (later illustrated by different invited speakers)
- Illustration of (a few) contributions to Cognitive Science/Psychology/Neuroscience debates through robotics experimentation.
OUTLINE

– 40s-70s History of Computer/AI/Cybernetics
– 70s « Classical » Robotics (top-down)
– 90s Subsumption/Animat (bottom-up)
– Now: Neuro-/Dev-/Embodied- Robotics
– Future: Convergence of approaches (hybrid)?

– Illustration of contributions of robotics to enrich/validate/refute biological and psychological hypotheses
40s-50s: Birth of computers

• ENIAC (1943) : 30 tons, 17 458 tubes, 70 000 resistors, 1500 relays, 6000 interrupters.

• Turing Test (1950).
1956: The birth of Artificial Intelligence

Workshop at Darmouth College:

- Minsky, Shannon, McCarthy, Newell, Simon.
- Newell and Simon: “logic theorist”; can prove simple theorems.
- Checkers playing softwares.

- Approval of the term “Artificial Intelligence”.
Initially, Artificial Intelligence was considered as:
« A set of computer programs which solve problems that are habitually solved by high-level mental processes in humans. »

But the robot is a machine
- Materialized (embodied)
- Acting in the real-world, thus situated.

Robot: rational deliberative and reactive agent.

Inter-acting and integrated functions.
Definition

• “the action of a robotic system is entrusted to a **locomotion** apparatus to move in the environment (wheels, crawlers, legs, propellers) and/or to a **manipulation** apparatus to operate on objects present in the environment (arms, end effectors, artificial hands), where suitable **actuators** animate the mechanical components of the robot. The perception is extracted from the **sensors** providing information on state of the robot (position and speed) and its surrounding environment (force and tactile, range and vision). The intelligent connection is entrusted to a **programming**, **planning** and **control architecture** which relies on the perception and available **models** of the robot and environment and exploits learning and skill acquisition. » (Siciliano & Khatib 08 Handbook Robotics)
50s: First bio-inspired robots!

Grey Walter’s tortoises:

- 50s: contemporary to the first computers!
- Uses vacuum tubes.
- Moves towards light sources.
- Stops and changes direction when hitting an obstacle.
50s: Grey Walter’s tortoises
Optimism and ambition of original AI

• « It is not my aim to surprise or shock you... But the simplest way I can summarize is to say but that there are now in the world machines that think, that learn and that create. Moreover, their ability to do these things is going to increase rapidly until – in a visible future – the range of problems they can handle will be coextensive with the range to which the human mind has been applied. »

Herbert Simon (1957)
1966-1973: AI’s rough landing

• These systems work well on simple problems ... but increasing the computation power was not sufficient to address real problems.

• Intractability
  – Approach at that time: testing all combinations (exponential type of complexity)
  – Note: the theory of algorithmic complexity has been developed in the 60s...
Example of symbolic AI approach

Opérateur Robot \( \rightarrow \) x :

Conditions:

Actions:
PRES-DE(ROBOT,x)

Opérateur Prendre(y) :

Conditions:
SUR(x,y)
PRES-DE(ROBOT,x)

Actions:
SUR(x,_)  
TIENT(ROBOT,y)
Difficulties and limitations...

• Requires all cases, scenarii and relevant features of the environment to be pre-identified by the Researcher (« closed world assumption »).

• Difficulty to integrate different cognitive functions at such a high-level.

...nevertheless worked on real robots!

- **66-72: Stanford’s Shakey robot**
- **Symbolic Intelligence (based on logic)**
- **Uses the sense-plan-act (SPA):**
  1. Sense: observes the situation with sensors
  2. Plan: builds a world model and uses it to plan its course of actions
  3. Act: performs the action
  4. Back to 1
Symbol Grounding Problem

• John Searle’s Chinese room experiment (1980) aimed at refuting a philosophical position that Searle named “strong AI”: « The appropriately programmed computer with the right inputs and outputs would thereby have a mind in exactly the same sense human beings have minds. »

• Besides the problem of exploding number of predicates led to define the “frame problem”: How to represent, in the framework of logic, the effects of an action without explicitly representing all the trivial ones but only the pertinent ones?
Gibson’s affordance theory (1977)

• Relation between the environment and the agent that affords the opportunity for that agent to perform an action.
O’Regan’s sensorimotor theory

Consciousness of feel

Experienced quality = sensorimotor law

Attending, cognitively accessing..

Also see Course on Active Perception by Bruno Gas.
O’Regan’s sensorimotor theory

“Red” is the way red things change the light
(Broackes, 1992; Philipona & O’Regan 2006)

jeudi 28 novembre 2013
Contribution of the body to cognition

Humanoid hand vs.

Anthropomorphcic Shadow Dexterous Hand (tm):
• 20 degrees of freedom, tactile/position/force sensors

Soft gripper

Cornell University gripper (Bongard & Pfeifer 2006):
• 1 degree of freedom
Contribution of the body to cognition

Active walker vs. Passive walker

Honda Asimo robot (2004) with preprogrammed walking behavior

McGeer (1990) IJRR
Intelligence without representation

• « I [...] believe that human level intelligence is too complex and little understood to be correctly decomposed into the right subpieces at the moment and that even if we knew the subpieces, we still wouldn’t know the right interfaces between them. Furthermore, we will never understand how to decompose human level intelligence until we’ve had a lot of practice with simpler level intelligences.» Rodney Brooks (1991). Artificial Intelligence, 47(1-3):139-159.

• « Elephants don't play Chess. » R. Brooks (1991)
The Animat Approach (1990)

• Bottom-up approach, bio-inspiration, maintenance of the agent in a region of viability.
• Control architectures with layers of incremental complexity, with each layer « compiling » and « integrating » perception/action (Evolution-like).
• Optimization through Reinforcement Learning (see Sigaud/Khamassi Course) or Evolutionary Algorithms (see Bredèche/Doncieux Course).
• Meyer & Wilson’s From Animals to Animats: Simulation of Adaptive Behavior Conferences.
1984: Braitenberg’s vehicles

- At the same time V. Braitenberg, a physiologist, presents, in a short but also revolutionary book, his point of view on intelligence.
- A set of thought experiments on how simple abstract vehicles.
- For instance:
  - 2 light sensors
  - 2 motors
- Connected with various combinations:
- Can exhibit rich behaviors!

- « When we analyze a mechanism, we tend to overestimate its complexity. » V. Braitenberg
- « Intelligence is in the eye of the beholder » R. Brooks
Brooks’ Subsumption Architecture &
Behavior-based Robotics

- Each behavior operates in parallel.
- Behaviors of higher priority inhibit the lower ones.
- The global behavior emerges from the interactions between the behaviors and the environment.

Genghis robot (MIT)
« Roomba » vacuum cleaner
(by Rodney Brooks’ AI Robot)
But behavior-based architectures rapidly become messy...
Generalization?

Also see Course on the Basal Ganglia as a central action selection component in the brain (Girard). But difficulties to learn priorities/sigma-pi through RL.
Experimental data: Insects and birds flying in front of artificial patterns; Recording of neural activity; ...

Conclusion: Insects and birds use optical flow (OF), velocity of the slip of the image on the retina.

To avoid obstacles: balance left & right (OF), like Braitenberg!
Bio-inspiration (obstacle avoidance)

Each eye component has its own EMD (Elementary Movement Detector).
Successive light stimulations (diameter 1μm) of the two horizontal photoreceptors
Bio-inspiration (obstacle avoidance)

- optronic angular velocity sensor,
- must move to see!
- tested on a real robot running at 50cm/s (Pichon et al. 1989)
Bio-inspiration (altitude control)

- Two light sensors: optical flow,
- V_x/h: altitude regulation (OF regulating),
- compensates for wind disturbances,
- take-off and landing capabilities for free (nose up or down commands are sufficient),
- integrated in a 100g robot.

(Ruffier & Franceschini, RAS 2005)
Bio-inspiration (altitude control)

Accounts for unexplained results:
• honeybees descend in a headwind,
• land with a constant slope,
• drown when travelling over mirror-smooth water.
• explains how insects manage to fly safely without any of the instruments used onboard aircraft to measure the groundheight, groundspeed, and descent speed.

See also Floreano et al. PNAS 2013.
Bio-mimetism (rat whiskers)

N’Guyen et al. 09; Pearson et al. 10; Mitchinson et al. 14
Bio-mimetism

• Octopus robot

• Ecce robot

• C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, P. Dario (2012) Soft Robot Arm Inspired by the Octopus *Advanced Robotics*

• R. Pfeifer, Josh Bongard, Don Berry.
Neuro-mimetism

- Brains have slow and fast loops
- Brains cope with uncertainty
- (See Courses of Arleo/Gaussier/Girard/Guigon/Khamassi)
Neuro-mimetism

Kenji Doya (2000)

Current Opinion in Neurobiology
Emergence of sensori-motor representations (Tani & Nolfi 1999)
Emergence of sensori-motor representations (Tani & Nolfi 1999)
Emergence of sensori-motor representations (Tani & Nolfi 1999)
Emergence of sensori-motor representations (Tani & Nolfi 1999)

(a) from step 130 to 300
(b) from step 380 to 550
(c) from step 820 to 990

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Navigation/Localization/Cartography

• Without a map (à la Braitenberg?)
• With a map:
  • Noisy sensors / perceptual ambiguity
• Localization: need to know the map.
• Cartography: need to know the position
• SLAM

(Also see Bessière’s Course)
Neuro-mimetic navigation

- Hippocampal place cells (e.g. Nakazawa, McHugh, Wilson, Tonegawa (2004) Nature Reviews Neuroscience)
- (Also see Arleo’s Course)
Role of the basal ganglia/dopamine in navigation learning

• Dopamine reward prediction error signals (Schultz et al., 1997)

• Dopamine reinforces synapses associated to performed action in the basal ganglia.

• (Also see Girard, Khamassi Courses)
Example: A simulated model of learning in the rat basal ganglia

\[ \delta_{t+1} = r_{t+1} + \gamma \cdot V(s_{t+1}) - V(s_t) \]

Behavioral Neurophysiology (Mulder et al 2004)  
Simple simulations (Khamassi et al 2008)  
Continuous simulations (Khamassi et al 2005)

Experiment on e-puck robot  
Physical simulations  
Computational model

Multi-module Neural Net

Khamassi - Robotic modelling approaches to Cognitive Sciences

CogMaster 05/03/2019
MULTIPLE DECISION SYSTEMS IN A NAVIGATION MODEL

Work by Laurent Dollé:
Dollé et al., 2008, 2010, 2018
Test on a « rat-robot » (EU FP6)

Work by:
Ken Caluwaerts (2010)
Steve N’Guyen (2010)
Mariacarla Staffa (2011)
Antoine Favre-Félix (2011)
Test on a « rat-robot » (EU FP6)

Hippocampal (H) strategy only

H strategy + BG strategy
Autre example: A neuro-robotic model of learning in monkey prefrontal cortex

Behavioral Neurophysiology (Quilodran et al. 2008)

Computational Modelling (Khamassi et al. 2014)

Autonomous Robotics (Khamassi et al. 2011)
Autre example: Reproduction of monkey performance

**A**

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**B**

- 4 monkeys: SEA REP
- robot: SEA REP
- simulation: SEA REP

Number of trials:
- 4 monkeys: 4
- robot: 4
- simulation: 4
Autre example: Reproduction of neural activity

- Anterior cingulate cortex (ACC) action value neurons
- Lateral prefrontal cortex (LPFC) neurons
- Chosen target

![Graphs and charts showing neural activity over time](image)

**Parameters:**
- \(\beta^*\)
- \(\beta/10\)
Lessons from these examples

• Expe with iCub robot were super-simplified, even though they were « embodied ». Still some output (behavioral predictions, dopamine neural activity).

• Navigation simulations were very complex, although they looked simple. This led to new predictions on the coordination of modules.

• Always navigate between different levels: connexionism, abstraction, discretization, symbolic, ... Maybe the brain is itself doing this.
Intrinsically Motivated Robots

The playground experiment (Oudeyer et al. 2004): Artificial curiosity mimicking child development by driving the robot towards interactions that maximise progress in predicting the actions’ consequences. (See Course of Oudeyer)
Intrinsically Motivated Robots

The playground experiment (Oudeyer et al. 2004): Artificial curiosity mimicking child development by driving the robot towards interactions that maximise progress in predicting the actions’ consequences. (See Course of Oudeyer)
Autopoietic system

• « An autopoietic machine is a machine organized (defined as a unity) as a network of processes of production (transformation and destruction) of components which: (i) through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produced them; and (ii) constitute it (the machine) as a concrete unity in space in which they (the components) exist by specifying the topological domain of its realization as such a network. »

• Maturana & Varela (1980). MIT Press
Gay, Georgeon & Mille’s Enactive Markov Decision Process (EMDP) and Enactive Cognitive Architecture.
Radical Interactionism

Emotion & Social Interaction

Robots interacting with autistic children.

See Course of Chetouani/Gaussier
Where are we now?

Exotic variations of robotics have now integrated the main stream (or had always been accepted...):

• Animat approach
• Multi-agent approach
• Neuro-robotics
• Reinforcement learning
• Statistical & probabilistic approaches
• Evolutionary robotics
• Social interactions
• Developmental robotics
Towards **Cognitive Robots?**

- Can we conceive cognitive robots, able to adapt, to understand, to switch contexts, levels & representations, to auto-evaluate, to generalize, to interact, to be self-aware?
  - 40s-70s Historique IA
  - 70s-90s Robotique « classique » (top-down)
  - 90s-00s Subsumption/Animat (bottom-up)
  - 00s-10s Neuro-/Dev-/Embodied- Robotics
  - **Now: Convergence of the approaches (hybrid)?**
Cognition viewed by Cognitive Systems Researchers

• « Cognition can be viewed as the process by which the system achieves robust adaptive, anticipatory, autonomous behavior entailing embodied perception and action. »

• « Meaning is a description attributed by an outside agent: it is not something that is intrinsic to the cognitive system except in the sense that the dynamics of the system reflect the effectiveness of its ability to interact with the world. »

• David Vernon et al. (2007)