Human-Robot Interaction
PhD course on Advanced Robotics

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Programme

- 5 lessons

- Motivation, foundations, philosophy, psychology, and some controversies

- From Human-Computer Interaction to Human Robot Interaction

- Metrics

- Psychology factors

- Detection, generation and representation of emotions

- Semiotics
References I

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Semiotics and Human-Robot Interaction
Introduction I

- Everyone doing robotics does, one way or another, HRI

- Highly speculative field

- Highly abstract frameworks tend to be difficult to instantiate

- Highly specific frameworks tend to be difficult to extrapolate
There is an obvious rationale to look at human-human relations (or at least to animal-animal relations) and try to extrapolate to HRI

—» Humans have been quite good at creating/transforming/destroying relations among them «—
HRI is "mainly" the study of *perception* and *action* maps

- Data exchanged between environment and robot
- Sensing devices
- Processing strategies, namely how to make them efficient
Introduction IV

... but also of the objects and relations between them

▶ What models for robots and environment?

▶ What properties for the relations?
A First on Human Models I

- Inspiration drawn from Psychology theories of Personality

- B.F. Skinner’s behaviorism
  - Organisms, interact with environment according to a reinforcement/penalty map
  - A behavior followed by a reinforcing stimulus results in an increased probability of that behavior occurring in the future
  - A behavior no longer followed by the reinforcing stimulus results in a decreased probability of that behavior occurring in the future
A First on Human Models II

- Maslow’s hierarchy of needs
  - [Physiological] Air, food, rest, shelter, etc
  - [Safety] Physical, economical, psychological, etc
  - [Love] Friendship, Social acceptance, etc
  - [Respect] Reputation, reconnaissance, self-respect, etc
  - [Self-realization] Self-imposed goals achieved, etc
  - [Knowledge] Comprehension, etc
  - [Aesthetic] Art does not need a purpose
From Human-Machine Interaction to Human-Robot Interaction I

- Until the 70’s there was not a clear need for research on relations between humans and machines

  Only a small number of relations was usually needed

- Research on Human-Computer Interaction (HCI) emerged around the 80’s, with the dawn of computers, and software development

  Necessary to measure the efficiency of common operations, e.g., project management/development, using some device to accomplish a task, etc

  Research was mainly on the establishment of "good" principles on how to use computers for a variety of tasks

  Fostered a number of practices/recommendations/standards on sw development
From Human-Machine Interaction to Human-Robot Interaction II

- Chronology points to almost a good number of milenia of explicit concerns on HRI
  - [850 bC] Héphaïstos, the Greek God of Fire, created artificial women to help him ... according to Homer (Odyssey)
  - [1600-1914] Artificial automata, most of them with clear anthropomorphic characteristics
From Human-Machine Interaction to Human-Robot Interaction III

- **[1927]** Metropolis, by Fritz Lang

- **[1970/80]** Star Wars, by George Lucas

- **[1982]** Blade Runner, by Ridley Scott

- **[2004]** I Robot, by Alex Proyas

In most of the cases in chronology the robots develop human emotions

Is this a projection behavior by the humans?
Usability of Interfaces in HCI

- Aims at measuring the quality of an interface
- Oriented to the implementation
- Defined in ISO 9241-11 (see [Bevan, Macleod, 1994])

"The effectiveness, efficiency, and satisfaction with which specified users achieve specified goals in particular environments"

See for instance [Seffah et al, 2006] for an additional discussion on several ISO standards related to usability
Usability of Interfaces in HCI II

- Usability can be defined by a set of attributes such as (see [Seffah et al., 2006] for additional attributes)
  - **Learnability**: How easy is it for users to accomplish basic tasks the first time they encounter the design?
  - **Efficiency**: Once users have learned the design, how quickly can they perform tasks?
  - **Memorability**: When users return to the design after a period of not using it, how easily can they reestablish proficiency?
  - **Errors**: How many errors do users make, how severe are these errors, and how easily can they recover from the errors?
  - **Satisfaction**: How pleasant is it to use the design?
A typical recommendation is to include usability goals already at design time (see [Bevan, Macleod, 1994]).

In addition, usability measures can also be fed back at runtime, e.g., to change the focus of the interface.
Utility of Interfaces in HCI

- Oriented to the results

- Utility and usability should be considered equally important

What’s preferable

- To have a high usability interface that does not help achieving the mission?

- To have a low usability interface that, nonetheless, manages to drive the user successfully to the goal?

- Some authors include utility as an attribute of usability
Objective: To develop performance metrics for motor behaviors such that the quality of interaction can be assessed during the execution of a task (see [Carroll, 2003]).

Hick-Hyman model

$$RT = a + b \log_2(n)$$

with $a$, $b$ constants empirically determined and $n$ the number of stimuli.
Evaluation of Motor Behaviors in HCI II

Keyboard model (1980) or Keystroke-Level Model (KLM); developed to predict the time it takes to a human to complete a task using a computer keyboard

\[ RT = t_K + t_P + t_H + t_D + t_M + t_R \]

Where

- \( t_K \): time to hit 1 key
- \( t_P \): time to localize 1 key
- \( t_H \): time to remove the finger from the key (homing)
- \( t_D \): time for planning
- \( t_M \): time for mental work
- \( t_R \): time for the system to respond

Common values: \( 0.08 \text{s} \leq t_K \leq 1.2 \text{s} \)
Fitt’s model for a task difficulty index (1954)

\[ ID = \log_2(2A/W) \]

with \(A\) is the amplitude of the movement necessary for the execution of the task and \(W\) is the target size.

This model is strongly similar to Shannon’s model for the capacity of a communication channel

\[ C = B \log_2(S/N + 1), \]

where \(S, N\) stand, respectively for the signal and noise power.
From HCI to HRI I

- Human factors in HCI controlling robots (see [Gertman, Bruemmer, 2008])

  Sensation, attention, cognition, effort, utility, physiological and psychological factors

  - Response consistency in terms of task demand

    Different tasks have preferable interfaces; the response of an operator must be consistent with the task at hand

    Example: Wall painting has different positioning accuracy requirements than catching a glass of water
From HCI to HRI II

- **Use of different modalities**

  The use of different sensory capabilities may help multi-tasking.

  Example: auditory and visual sensing are processed in different regions of the brain which may indicate that interfaces making simultaneous use of these two channels may improve efficiency.

- **Stimulus response considerations**

  The Hick-Hyman and Fitt's models need to be accounted for.

- **Visualization factors**

  - **Provide abstraction to support cognition**

    Abstraction tends to reduce the number of stimuli and hence (Hyck-Hyman model) improves reaction time.
From HCI to HRI III

- Promote task based perception in 3D world

  Perception is improved if perceptual cues are provided in a 3D environment, e.g., the sense of depth in an image

- Supply navigation metaphors

  Analyzing a scene for perceptual cues that can be used to take navigation decisions tends to be much more efficient than the hard processing of sensory raw data

- Link metaphors to affordances

  Affordances indicate the preferable actions associated with a metaphor
From HCI to HRI IV

- Design computer-generated maps to be compatible with human cognitive maps
  
The goal is to make the understanding of the sensory data easy; too much data tends to decrease good perception

- Select representations that reflect operator attention, expectancy, and value
  
Adapt the interface/interaction to the knowledge level of the operator
Good Practices When Designing HRI Systems I

- Adapted from [Goodrich, Olsen, 2003]

- Metrics for autonomy
  - Neglect time (NT)
    Measures the decrease in the effectiveness of a robot as it is neglected
  - Interaction time (IT)
    Measures the increase in the effectiveness of a robot as the interaction time between a user and a robot increases
Good Practices When Designing HRI Systems II

▶ Robot attention demand (RAT)

\[ RAT = \frac{IT}{IT + NT} \]

▶ Free time (FT)

\[ FT = 1 - RAD \]

▶ Fan out (FO)

Measures how many robots can be effectively controlled by a human

\[ FO \leq \frac{1}{RAD} \]
7 principles to make interactions efficient

1. Implicitly switch interfaces and autonomy clues

   Multiple interfaces to interact with a robot may have different effectiveness characteristics; the idea is to switch among them as needed in order to maximize effectiveness

2. Let the robot use natural human cues

   Include/use semantics knowledge in the interfaces, eventually derived from mental models
3. **Manipulate the world instead of the robot**

   Interfaces should be oriented towards the execution of the task (and not to draw attention to the robot or the interface itself)

   Eventually use mental models specific to interact with the world and with the robot

4. **Manipulate the relationship between the robot and world**

   Try to use effective relationships to express the interactions between robot and world; eventually these need not to be realistic at all

5. **Let people manipulate presented information**
6. **Externalize memory**

   The interface must integrate all the information in a model that can be quickly perceived by users.

7. **Help people manage attention**

   The interface must autonomously emphasize the proper information to minimize eventual perception errors by the user.
Summary - Relations Between the Key Concepts in This Lecture

- Abstract frameworks
- Human factors
- Models of human behavior

- HRI
- HCI
- HMI

- Interaction quality metrics
A Sequence of Basis Questions on HRI I

1. Is there an architecture for a truly intelligent robot?

2. Does any of the following expressions hold?

\[
\text{Intelligence} \implies \text{Quality HRI}
\]

\[
\text{Intelligence} \iff \text{Quality HRI}
\]

3. What’s intelligence? What are the requirements for intelligence?

4. **Tentative claim:** The models of human behavior/personality/motivation are a natural area where to search since humans are pretty good at interacting with each others
5. What are the right objects to construct such models?

6. **Tentative answer:** Objects must be able to
   - Accommodate meanings (semantics)
   - Must have some form of representation
   - Must have some form of implementation
Interaction and Architectures I

- Robot control architectures are enablers for HRI

- There are tight relations between architectures and programming methodologies

- The subsumption architecture (see [Brooks, 1985]) is sometimes referred as an "elegant form of programming"
Interaction and Architectures II

- Building blocks can easily be identified with object constructs in object oriented programming languages

- The subordination between levels matches Psychology models, e.g., Maslow's hierarchy of needs (see [Maslow, 1970])

- Semantics is embedded into the blocks
  - Each block "knows" its task
  - Each block "knows" the protocol by which it communicates with the rest of the network of blocks
Programming Languages I

- Imperative (C(*), Java, Fortran, Pascal, ...)

- Declarative (Prolog, Lisp, ...), there exists an inference engine to evaluate the sequence of instructions

- Modeling languages (UML, Petri Nets, Flowcharts, VRML, XML, ...), more generally, anything that can be described by a graph, i.e., with "objects" and "relations" between them

Data structures are, in general, close to the language main constructs whereas in imperative languages is often required that suitable data types and structures be defined prior to implementing some form of engine to process these structures
In all languages, the handling of semantics is in general poor.

Semantics representation is in general embedded rigidly in datatypes and ...

... it is not practical to extract datatypes from arbitrary raw data ...

Semantics processing is embedded in the generic processing; in general it is not easy to reason over the semantic content of objects as humans do.

**Tentative claim:** The ability to process semantics is what distinguishes humans from robots.
"Metrics" for HRI I

- One can only think about metrics once the space over which the metrics are to be defined is known.

- Segment the activities of people and isolate a number of "micro-behaviors" (eye gaze, eye contact, specific gestures, actions such as approaching the robot and move away, vocalize, repetition, ..., other).
"Metrics" for HRI II

Analyze the relative frequency of each micro-behavior (see [Dauntenhahn, Werry, 2002] on the use of robots to improve interactions of autistic children - 14 micro-behaviors were used)

Figure 2: Histogram showing comparative eye gaze behaviours of seven children directed towards robot and truck. Averages and standard deviations (dotted lines) are shown.

Figure 3: Histogram showing comparative eye gaze behaviours in terms of percentages (total duration of eye gaze behaviour in relation to the duration of the section).

Figure 4: Scatter plot with average behaviour lengths robot/truck. Groups can be identified: group one (circle), two (square) and three (triangle). Averages and standard deviations (dotted lines) are shown.
"Metrics" for HRI III

Similar quantitative approach used in [Michaud et al, 2004] for robots interacting with toddlers (child gaze direction, physical contact, displacement of child)

Fig. 1. First Robot prototype (left) and a 10-month old infant interacting with Robal (right).

Fig. 5. Scatter plot of the observed gaze direction of the children toward Robal, compiled for A-B protocol and B-A protocol.

Fig. 7. Scatter plot of the observed displacement of the child, compiled for A-B protocol and B-A protocol.

Fig. 6. Scatterplot of the observed physical contact by children with Robal, compiled for A-B protocol and B-A protocol.
"Metrics" for HRI IV

Similar quantitative approach used in [Giusti, Marti, 2008]; the duration of speech in 5 categories is measured (talking to PARO as agent, talking to others about PARO as agent, talking to others about PARO as non-agent, talking to others about PARO as agent/non-agent, generic talking)

<table>
<thead>
<tr>
<th>TABLE 3</th>
<th>GROUP AREA A (SEVERE)</th>
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<tbody>
<tr>
<td></td>
<td>S4</td>
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<tr>
<td>TPA</td>
<td>578</td>
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<tr>
<td>TOA</td>
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</tr>
<tr>
<td>TOnonA</td>
<td>0</td>
</tr>
<tr>
<td>TOnonAA</td>
<td>0</td>
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<tr>
<td>GS</td>
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<td>LTS</td>
<td>880</td>
</tr>
<tr>
<td>LTO</td>
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TPA: Talk to Paro as an Agent; TOA: talk to others about Paro as an Agent; TOnonA: Talk to others about Paro as non-Agent; TOnonAA: talk to others about Paro as an agent/non-agent; GS: General Speaking; LTS: length of the total speech; LTO: length of the total observation.

<table>
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<td>TOA</td>
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<tr>
<td>TOnonA</td>
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<tr>
<td>TOnonAA</td>
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</tr>
<tr>
<td>GS</td>
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<td>LTO</td>
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</tr>
</tbody>
</table>

TPA: Talk to Paro as an Agent; TOA: talk to others about Paro as an Agent; TOnonA: Talk to others about Paro as non-Agent; TOnonAA: talk to others about Paro as an agent/non-agent; GS: General Speaking; LTS: length of the total speech; LTO: length of the total observation.

Fig. 1. A group of subjects interact with Paro in the A arc.
Each interaction has a target and it is possible to define at each instant a distance to this target

It is possible to define a Fitt’s measure for each interaction
The URUS Example I

- Pioneer wheeled robot
- Robot head and torso developed by Scuola Superiore Sant’Anna and RoboTech, Pisa, Italy
- Does this setup allows quality HRI?
Evaluation by Likert Questionnaire

- The questionnaire consisted of:
  
a) 4 questions in Likert scale:

1) I liked to interact with the robot
2) The robot scares me
3) I like the robot physical appearance
4) It's been easy to interact with the robot

b) 1 multiple choice test:

5) What did you like most during the interacting with the robot? Possible answers: a) The physical appearance, b) the facial expressions, c) the voice, d) the touch-screen.

C) 1 closed questions:

6) Interacting with the robot has been more like interacting with a machine or with a human being?

- The above is an example of a 5-points questionnaire

- 7-point and 10-point questionnaires are also commonly used
Evaluation by Likert Questionnaire II

Question no. 1: “I liked to interact with the robot”

Question no. 2: “The robot scares me”

Question no. 3: “I like the robot physical appearance”

Question no. 4: “It’s been easy to interact with the robot”
Question no. 5
“What did you like most during the interacting with the robot?”

Question no. 6
“Interacting with the robot has been more like interacting with a machine or with a human being?”

![Chart 1](image1.png)

![Chart 2](image2.png)
Human-Dependent (unactuated robots) that simply want to get from one place to another

Are humans willing to help an handicapped robot?
Social Robotics I

- Interaction quality is very much dependent on the quality of perception (sensing)

  Interactions in lab environment tend to be simpler than in real environment (see the example in [Kanda et al, 2004])

- Multiple examples in the literature
  - Museum tour guide robots (see [Thrun et al, 1999])
  - Companion robots, e.g., the Paros seal (see [Wada et al, 2008])

Fig. 2. Paro, the seal robot.
Social Robotics II

- Robots encouraging Japanese children to learn English (see [Kanda et al, 2004])

A robot is placed in a basic school to interact with children

- Receptionist robots, e.g., Saya, Actroid

  - Understands a basic number of sentences
  - Expresses emotions of surprise, fear, anger, revulsion, happiness and sadness

  - Understands a basic number of sentences
  - Expresses several emotions through facial expressions
Behaviors in Social Robotics

- Acceptable/reasonable behaviors are very much dependent on cultural aspects

- Robots create expectations on people they interact with

  In general, the effect of a robot on individuals changes over time, meaning that adaptation/learning strategies are required for robots interacting with humans

- Models of human-human interactions suggest that there are different proximity zones each requiring a specific response/behavior by the robot (see [Hall, 1966])
  - Human-human conversational distance is within 1.2 m
  - Human-human common social distance for a person just met is within 1.2 and 3.5 m
  - Human-robot distance is within 0.5 m
The Uncanny Valley Paradigm I

- Hypothesizes that when robots look and act *almost* as humans the emotional response by the humans with whom the robot interacts decreases (stated by Masahiro Mori in *Bukimi no Tani Gensho*, 1970)

The Uncanny Valley Paradigm II

- Not consensual among people doing robotics

- Not clear if the valley is induced uniquely to a human-machine factor or can be generated by personal beliefs on what is the "normal" human appearance

- In general, experiments do not decouple the influence of motion on emotional response and hence the true value of anthropomorphism may not be obtained by the HRI metrics
The Uncanny Valley Paradigm III

- Plain robot appearance can be a catalyst for improved interaction

Some studies show scenarios where autistic children prefer the plain robot appearance to a doll-like appearance (see [Robins et al, 2004])
The valley may even turn into a cliff

[Bartneck et al., 2007] measured the *likeability* of several anthropomorphism degrees, namely "real human", "manipulated human", "computer graphic", and "android" (using a questionnaire handed to 58 people).
The Uncanny Valley Paradigm V
▶ http://www.dotolearn.com/games/facialexpressions/face.htm

Do you fancy interacting with this robot?
The Uncanny Valley Paradigm VI

▶ http://www.robotcub.org

Figure 4: iCub facial expressions
Uncanny Questions ? I

- What’s the *utility* of having a face expressing an emotion vs. a display texting that very same emotion?

![I’m angry](image)

- Probably this is at the edge of the uncanny cliff!

What’s the most effective expressing the emotion?
Uncanny Questions II

- What’s the point having a high/low emotional response/likeability/familiarity?

Some authors see emotions as a tool to reduce the complexity of decision making (see [Suzuki et al, 1998])

![Diagram](image)

*Figure 2. The agent architecture for multimodal environment*
Emotions I

- A definition of emotion is not consensual among roboticists

- "Emotions are biological state variables that provide estimates of goodness", [Meystel, Albus, 2002]

Provide criteria for decision making and hence are an indicator of intelligence

"... Without value judgements to support decision making, nothing can be intelligent, whether or not is biological and artificial ..."
Emotions II

- Psychology clearly separates emotions from individual intelligence (see for instance [Goleman, 1995])
  - Intrapersonal intelligence - High IQ (Intelligent Quotient) people may have problems interacting with others (low EQ - Emotional Quotient)
  - Interpersonal intelligence - Even small IQ people may be highly successful interacting with others (high EQ)

- Are emotions really needed?

  Emotions combine explicit with implicit communication, [Rani, Sarkar, 2004]
Emotions III

Figure 1. Human-Robot Interaction Architecture
It seems that the answer is, yes, ... but ...

In social environments the influence of emotions may be moderated by cultural values, [Butler et al, 2007]

What’s culture for a robot?
Representing Emotions: The AVS space I

- This space encodes emotions into 3 coordinates named Arousal, Valence, Stance (see for instance [Jensen et al, 2002, Jensen et al, 2003])

- An emotion is a region of the space

- Arousal - Triggering of emotions

- Stance - Mental attitude

- Valence - Capacity for combination
Representing Emotions: The AVS space II

- Sensor data is mapped into the AVS space using look-up tables

<table>
<thead>
<tr>
<th>Table 4: Sensor inputs and corresponding affects</th>
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<tr>
<td><strong>Signal Type</strong></td>
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</tr>
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</tbody>
</table>

- The affects resulting from sensors are combined and the resulting point in the AVS space is mapped into a set of parameters used to control the expressiveness of the robot
Representing Emotions: A 2D model

- 4 basis emotions, [Suzuki et al, 1998]

- Features extracted from sensor data are input to a Self-Organizing Map (Kohonen map)

- The map tends to organize by regions representing the emotions
Representing Emotions: A 2D model II

- The emotional state of the robot results from the combination of the amount of each emotion in the SOM and it is mapped into actions by the robot.

- In a sense, emotions are just a sensor-to-actuator map.

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*Figure 2: Overall expressions generator process from sensors entries to actuators.*
The goal is to look for cues in moving humans/robots/objects and extract intentions from the motion.

In general no hidden meanings are extracted.

More focused on detecting/recognizing activities.

Typical paradigms are often used:

- A priori define a set of features to be recognized from sensed data.
- Define a classifier able to discriminate among the features.
- The meanings are embedded in the features ...

The combination of Vision+Hearing+Touch provides the richness of human sensing (Smell and Taste sensors are not yet common).
Emotions and Affective HRI II

People detection and tracking

Head detection to estimate gaze and focus (see for instance [Valibeik et al, 2009])

Gaze and focus provide a good indication on the location of the focus of attention of humans

The probabilistic reasoning is just a Bayesian network
Facial expressions
(from [Ge et al, 2008])

Determines the motion of a number of key points in the face after the Facial Action Coding System and models the motion as a non-linear mass-spring system.

Discriminate among emotions using the Support Vector Machines (close connections with neural networks)
Expressiveness of Motion I

- The expressiveness of a trajectory/path is often related to the level of chaos/entropy

- Typical measures for the degree of "order/chaos" in a trajectory include
  - Fractal dimension of the trajectory
  - Lyapunov exponents for the trajectory
  - Fourier components for the trajectory
Expressiveness of Motion II

- An architecture to measure expressiveness (see [Sequeira, 2008])

- Some authors suggest a linear combination of expressiveness features

\[ E = c_1 e_1 + c_2 e_2 + c_3 e_3 + c_4 e_4 + \cdots \]

For the case of a data model (see [Ceruti, Robin, 2007])

- \( e_1 \) stands for the number of data elements in the model
- \( e_2 \) stands for the fan-out of high level entities in the model
- \( e_3 \) stands for the count of synonyms of an entity in the model
- \( e_4 \) stands for the number of queries supported by the model
Getting Real Values for HRI "Metrics"

- Analysis of micro-behaviors (duration, relative frequency, etc)
- Likert like questionnaires
- Success / Failure of interaction experiments
- Expressiveness

More generally, any (arbitrary) combination of relevant features will do
Issues on Getting Real Values for HRI "Metrics" I

- In general the detection/recognition of relevant features is a difficult problem
  - Vision has intrinsic problems in most approaches, e.g., computational, lighting
  - Ultrasounds have angular accuracy issues and are prone to reflections
  - Laser range finders do not detect transparent surfaces
  - Wheels/Crawlers may slip and induce odometry errors
  - ...

- Robustness requirements often requires the fusion of multiple sensors

  Different fusion methods have different dynamics
  - EKF based methods may have convergence issues
  - Particle filters may have computational issues
  - Covariance intersection may have overoptimism issues
Issues on Getting Real Values for HRI "Metrics" II

- HRI "metrics" are thus likely to be biased by the dynamics of the measurement processes

  ↓

  **HRI metrics** should be instead **HRI utilities** in order to allow preference ordering and rational decision making

  Somehow this claim agrees with the previous one on the multiple ways to measure expressiveness
Frameworks for Social Robotics I

- A framework is a collection of components/functionalities required for HRI

- Frameworks/architectures very much "tied" to functional components

- Should a HRI system be developed from functionalities (with high level concepts defined a posteriori) ?

- Should a HRI system be developed from high level concepts (with deployment dependent on the tools chosen to implement the concepts) ?
Frameworks for Social Robotics II

▶ Home service robot, from [Lee et al, 2005]
Frameworks for Social Robotics III

- Personal robot, from [Salichs et al, 2006]
Frameworks for Social Robotics IV

- Paros robot, [Wada et al, 2008]

- Internal states describe emotions and change according the stimuli received.
- Behaviors generate control references which are parameterized by the emotional state the seal is in.
Software Design Patters for HRI ([Kahn et al, 2008])

1. "Patterns are specified abstractly enough such that many different instantiations of the pattern can be realized in the solution of the problem"

2. "Patterns can be often combined"

3. Less complex patterns (from the standpoint of an organizational structure) are often hierarchically integrated into more complex patterns"

4. Design patterns are fundamentally patterns of human interaction with physical and social world"
Typical patterns used for HRI: "The initial introduction", "Didactic communication", "In motion together", "Personal interests and History", "Recovering from mistakes", "Reciprocal Turn-Taking in game context", "Physical intimacy", "Claiming unfair treatment or wrongful harms"
Neat idea but quite similar to the usual notion of behavior
Category theory (CT) provides a suitable framework to represent the objects and relations among them.

A model of a hierarchy of abstractions (the level of abstraction increases towards the righthand side of the diagram).

The $H_i$ objects represent the data perceived by the robot at each abstraction level.
The $abst_i$ functors define the data processing between levels.

The $beh_i$ functors represent the decision processes on the perceived data.

The $A_i$ objects contain the information that directly affects the motion of the robot.

The $act_i$ functors stand for the processes that transform high level information into actuator controls.

The circle arrows indicate endofunctors in each of the categories involved.

At the lowest level of abstraction:

- $H_0$ includes objects such as configuration spaces.
- $A_0$ contains the control spaces.
- $beh_0$ account for low level control strategies, e.g., motor control feedback loops.
Coordinate transformations are examples of endomaps in $H_0$.

At the intermediate levels the $H_i$ can represent data, services, and functionalities such as path planning and world map building algorithms.

At the highest level of abstraction, $H_n$ stands for the objects used in natural interactions, that is, information units exchanged during natural interactions such as those occurring when using natural language. The $A_n$ stands for high level processing of such units.
Semiotics is a branch of general philosophy addressing the linguistic interactions among humans.

Semiotic signs evolved mainly from the work of C. S. Pierce and F. Saussure (see for instance [Chandler,2002, Bignell,2002]).

Humans use *semiotic signs* as basis information unit to interact among themselves.

Interaction using natural language is probably the most complete example of interaction among heterogeneous agents using semiotic signs.

The signs and morphisms defined among them form *sign systems*.
Following C. Pierce, signs can be of 3 categories

(i) Symbols, expressing arbitrary relationships, such as conventions,

(ii) Icons, such as images,

(iii) Indices, as indicators of facts or conditions

Signs defined in these three categories can represent any of the abstract entities, of arbitrary complexity, that are used by humans in linguistic interactions, [Bignell,2002]

A generic semiotic sign encapsulates three atomic objects, named meaning, object, and label, and the relations between them.
Signs II

Under reasonable assumptions on the existence of identity maps, map composition, and composition association, signs can be modeled as a category.

The SIGNS category can be identified as the “semiotic triangle”, is often used in the literature on semiotics (see for instance [Chandler, 2002]).

![Diagram of the semiotic triangle]

where

- *Labels*, (L), represent the vehicle through which the sign is used
- *Meanings*, (M), stand for what the users understand when referring to the sign,
Signs III

- **Objects**, (O), stand for the real objects signs refer to
- **semantics** are morphisms standing for the map that extracts the meaning of an object
- **syntactics**, standing for the map that constructs a sign from a set of syntactic rules
- **pragmatics**, standing for the maps that extract hidden meanings from signs, i.e., perform inference on the sign to extract the meaning
In Robotics a functor assigns to each object in SIGNS objects in a category ACTIONS where the objects are meaningful in what concerns the purpose of the robots (see [Sequeira, Ribeiro2007])

\[(q_0, a, B_a) \xrightarrow{\text{semantics}} (q_0, B_a)\]

\[A \xrightarrow{\text{synctatics}} \xleftarrow{\text{pragmatics}}\]

where

- \(A\) represents the practical implementation of a semiotic sign
- \(q_0\) stands for an initial condition that marks the creation of the semiotic sign, e.g., the configuration of a robot,
- \(a\) stands for a process or algorithm that implements a functionality associated with the semiotic sign, e.g., a procedure to compute an uncertainty measure at \(q_0\),
Deploying Semiotics Components II

- $B_a$ stands for a set in the domain space of $a$, e.g., a compact region in the workspace.

- A practical way to read ACTIONS is to consider the objects in $A$ as having an internal structure of the form $(q_0, a, B_a)$ of which $(q_0, B_a)$ is of particular interest to represent a meaning for some classes of problems.

- The *syntactics* morphism is the constructor of the object; it implements the syntactic rules that create an $A$ object.

- The *semantics* morphism is just a projection operator.

- The *pragmatics* morphism implements the maps used to reason over signs.

  For instance, the meaning of a sign can in general be obtained directly from the behavior of the sign as described by the object $A$ (instead of having it
Deploying Semiotics Components III

extracted from the label - a form of inference is named *hidden meaning* in semiotics

- The objects in ACTIONS can be extended to include additional components expressing events of interest
Towards a New Psychology for HRI?

- Some researchers advocate that a new psychology is needed to study HRI (see, for instance [Turkle et al, 2006])

‘Heinz Kohut describes how some people may shore up their fragile sense of self by turning another person into a self object.

In the role of self object, the other is experienced as part of the self, thus in perfect tune with the fragile individual’s inner state. Disappointments inevitably follow. Relational artifacts (not only as they exist now but as their designers promise they will soon be) clearly present themselves as candidates for such a role. If they can give the appearance of aliveness and yet not disappoint, they may even have a comparative advantage over people, and open new possibilities for narcissistic experience with machines. One might even say that when people turn other people into self-objects, they are making an effort to turn a person into a kind of spare part. From this point of view, relational artifacts make a certain amount of sense as successors to the always-resistant human material.’

- So, ... interesting times for Roboticists if robots start visiting Psychologists ... 😊