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Part V - Applications of Robotic Systems

Human-robot Interaction and Robot Control

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Abstract

The ever increasing desire for fully autonomous robotics triggered in recent years the interest in the study of the interactions between robots and between humans and robots. The long term goal of this research field is the operation of heterogeneous teams of robots and humans using common interaction principles, such as a common form of natural language.

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Human-Robot Interaction and Robot Control

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Abstract

This paper describes a robot control architecture with an underlying human-robot interaction (HRI) model. The architecture is supported on an algebraic framework inspired in semiotics principles.

The architecture is composed of a set of objects that capture, in the locomotion context, features often present in human-human interactions, namely ambiguity and semantics. The resulting framework differs from other works in this area in that it yields an algebraic system upon which more sophisticated control structures can be defined.

1 Introduction

The ever increasing desire for fully autonomous robotics triggered in recent years the interest in the study of the interactions between robots and between humans and robots. The long term goal of this research field is the operation of heterogeneous teams of robots and humans using common interaction principles, such as a common form of natural language.

The paper explores the fundamentals of a robot control architecture tailored to simplify the interactions between a robot and the external environment, containing humans and other robots. The approach followed defines (i) a set of objects that capture key features in human-robot and robot-robot interactions and (ii) an algebraic structure with operators to work on this space of the objects.

In a broad class of robotics problems, such as surveillance in wide open areas and rescue missions in catastrophe scenarios, the interactions among robots and humans are a key issue. In such real missions contingency situations often arise which may force robots to request help from an external agent, in most cases a human operator. The use of HRI that mimics human-human interactions is likely to improve the performance of the robots in such scenarios.

Interactions among humans and robots in semi-autonomous systems are often characterized by the loose specification of objectives. This is also a common feature in natural languages used in human-human interactions and accounts both for ambiguity and semantics[3]. The framework described in the paper handles robot-robot and human-robot interactions in a unified way thus avoiding the need for different skills for each of them.

The paper is organised as follows. Section 2 briefly describes how human-robot interaction has been accounted by relevant paradigms in the literature. Section 3 presents key concepts from semiotics

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[3] Ambiguity is related to errors in the meaning associated with an object, e.g., the precise meaning of the object is not accurately known. Semantics expresses the ability of a concept to have different correct meanings.

to model human-human interactions and motivates their use to model human-robot interactions. These concepts are then used in Section 4 to propose an architecture first in terms of free mathematical objects and next in terms of concrete objects. Section 5 presents a set of experiments that illustrate the main ideas developed along the paper. Section 6 presents the conclusions and some research directions.

2 A brief state of the art on HRI

HRI has been always present in robotics either explicitely, through interfaces to handle external commands, as in [13], or implicitely, through task decomposition schemes that map high level mission goals into motion commands, as in [22].

Behavioral techniques have been used in [27] to input mission specifications for a robot, in [23] to have a robot capable of expressing emotions and in [2] to make a robot join a group of persons behaving as one of them. In [20] the robots are equipped with behaviors that convey information on their intentions to the outside environment. These behav The CAMPOUT architecture for groups of heterogeneous robots, [11], is also supported on a hierarchy of behaviors. These are constructed using behavior composition, coordination and interfacing subsystems. The interaction among the robots is achieved with the exchange of both explicit data, such as state, and implicit, by having behaviors in charge of observing the environment for changes caused by the teammates. The MACTA architecture, [3], is also behavior based, with the HRI handled by a reflective agent that interfaces the robot and the environment. This agent decomposes a high level goal into planning primitives and the corresponding execution schedule. The MAUV architecture, [1], uses a sense-process-act loop, based on Artificial Intelligence techniques, to perform task decomposition from high level goals to low level actions. A hybrid, deliberative/reactive architecture is presented in [15], based on a functional hierarchy with planning, sequencing and skill managing layers. The HRI is implemented through standard viewing and teleoperation interfaces.

Often, humans are required to have specific skills to properly interact with the robots, e.g., be aware of any motion constraints imposed by the kinematics. High level primitives can be used to encapsulate such aspects and reduce the required skills. A robot for disabled persons, working with a reduced set of high level motion primitives, has been presented in [22].

High level commands have been used as a crude natural language for HRI. Human factors, such as the anthropomorphic characteristics of a robot, are a key subject in HRI as humans tend to interact better with robots with human characteristics, [14]. agents such as the robot following a human without having been told explicitly to do so. Natural language capability is undoubtedly one of such characteristics, this being an issue currently being tackled by multiple researchers. In [4] a spatial referencing language is used by a human to issue commands to navigate a robot in an environment with obstacles. The basic form of language developed in [12] converts sensor data gathered by multiple robots into a textual representation of the situation that can be understood by a human.

If the humans are assumed to have enough knowledge on the robots and the environment standard (imperative) computer languages can be used for HRI. This easily leads to complex communication schemes relying on protocols with multiple abstraction layers. As an alternative, declarative, context dependent, languages, like Haskell, [21] and FROB, [9, 10], have been proposed to simulate robot systems and also as a mean to interact with them. BOBJ was used in [8] to illustrate examples on human-computer interfacing. RoboML, [16], supported on XML, is an example of a language explicitly designed for HRI, accounting for low complexity programming, communications and knowledge representation.

3 A semiotic perspective for HRI

In general, robots and humans work at very different levels of abstraction. Humans work primarily at high levels of abstraction whereas robots are usually programmed to follow trajectories, hence operating at a low level of abstraction. Common architectures implement the mapping between abstraction levels using a functional approach by which a set of interconnected building blocks exchange information. The composition of these blocks maps the sensorial data into the actuators. Using category theory (CT) terminology,[4] an architecture lifts the information from the environment to the robot, as in the following diagram,

$$\begin{tikzcd}
 & \mathit{robot} \arrow[dr, "f_{actuation}"] & \\
\mathit{environment} \arrow[ur, "f_{perception}"] \arrow[rr, "\mathbf{1}_{environment}"] & & \mathit{environment}
\end{tikzcd} \tag{1}$$

and simultaneously retracts the information from the environment to the robot,

$$\begin{tikzcd}
 & \mathit{environment} \arrow[dr, "g_{perception}"] & \\
\mathit{robot} \arrow[ur, "g_{actuation}"] \arrow[rr, "\mathbf{1}_{robot}"] & & \mathit{robot}
\end{tikzcd} \tag{2}$$

The above category diagrams show two different perspectives of the well known sense-process-act loop. Diagram (1) represents the way the environment[5] sees the robot whereas diagram (2) represents the same for the robot. The maps $f_{actuation}$ and $g_{perception}$ represent the maps implemented by the architecture. The effect of the environment on the robot, represented by the maps $f_{perception}$ and $g_{actuation}$, has to be known for the above diagrams to commute. Thus, architecture design corresponds to the classical CT problem of, given an architecture proposal defined through $f_{actuation}$ and $g_{perception}$, to solve the corresponding determination and choice problems.

In some sense, diagrams (1) and (2) establish a sort of bounds on the design of robot control architectures. Namely, $f_{perception}$ represents the limits, set by the environment, on the perception of the environment by the robot. Similarly, $g_{actuation}$ represents the constraints, imposed by the robot, on the perception of the robot by the environment.

Semiotics is a branch of general philosophy that studies the interactions among humans, such as the linguistic ones, (see for instance [7] for an introduction to semiotics). Along the last decades semiotics has been brought to intelligent control and then it naturally spread to robotics (see for instance [18]). Different paradigms motivated by semiotics have been presented to model such interactions. See, for instance [17] on algebraic semiotics and its use in interface design, [19] on the application of hypertext theory to World Wide Web, or [6] on machine-machine and human-human interactions over electronic media (such as the Web).

The idea underlying semiotics is that humans communicate among each other (and with the environment) through signs. Slightly different definitions of sign have been presented in the literature on semiotics. Roughly, a sign encapsulates a meaning, an object, a label and the relations between them. Sign systems are formed by signs and the morphisms defined among them (see for instance [17] for a definition of sign system) and hence, under reasonable assumptions on the existence of identity maps, map composition, and composition association, can also be modeled by CT.

---

[4] Throughout the paper CT is used as the underlying tool supporting the proposed architecture, and clarifying the relations among the objects therein.

[5] The environment contains any relevant entity external to the robot, e.g., other robots and humans.

The following diagram, suggested by the "semiotic triangle" diagram common in the literature on semiotics (see for instance [5]), expresses the relations between the three components of a sign.

$$\begin{tikzcd}
 & M \arrow[dr, "\mathit{pragmatics}^\star"] & \\
L \arrow[ur, "\mathit{semantics}"] \arrow[rr, dashed, shift left, "\mathit{syntactics}"] & & O \arrow[ll, dashed, shift left, "\mathit{syntactics}^\star"] \arrow[dl, "\mathit{pragmatics}"] \\
 & M \arrow[ul, "\mathit{semantics}^\star"] &
\end{tikzcd} \tag{3}$$

Labels, (L), represent the vehicle through which the sign is used, for instance an algorithm. Meanings, (M), stand for what the users understand when referring to the sign. The Objects, (O), stand for the real objects signs refer to.

The morphisms in diagram (3) represent the different perspectives used in the study of signs. Semiotics currently considers three different perspectives: semantics, pragmatics and syntactics, [19]. Semantics deals with the general relations among the signs. For instance, it defines whether or not a sign can have multiple meanings. Pragmatics handles the hidden meanings that require the agents to perform some inference on the signs before extracting their real meaning. Syntactics defines the structural rules that turn the label into the object the sign stands for. The starred morphisms are provided only to close the diagrams (the "semiotic triangle" is usually represented as an undirected graph).

Following C.S. Pierce, signs can be of three classes, [6, 17], (i) symbols, expressing arbitrary relationships, such as conventions, (ii) icons, such as images, (iii) indices, such as indicators of facts or conditions. Symbols are probably the most common form of signs in robotics. For instance, state information exchanged among robots in a team is composed of symbol signs. Icons are often used by humans in their interactions, (e.g., an artistic painting can be used to convey an idea) and are also often found in robotics. For example, topological features can be extracted from an image and used for self-localisation. Indices are also often used among humans, e.g., in literary texts and when inferring a fact from a sentence. As a typical example, "the robot has no batteries" can be inferred from the observation "the robot is not moving". Similarly, "the robot is moving away from the predefined path" can lead to the deduction that "there must be an obstacle in the path".

The HRI model considered in this paper uses primarily symbols as basic data units for communication between a robot and its environment. Iconic information (images) will also be used, though morphed into symbols.

4 An architecture for HRI

This section introduces the architecture by first defining a set of context free objects and operators on this set. Next, the corresponding realizations for the free objects are described.

Diagram (3) provides a roadmap for the design of a control architecture and a tool for the verification that the sign system developed in the paper is coeherent with the semiotic model of human-human interactions.

The proposed architecture includes three classes of objects: motion primitives, operators on the set of motion primitives and decision making systems (on the set of motion primitives). The sign model (3) is used to design the motion primitives objects.

The ambiguities common in human-human interactions amount to say that different language constructs can be interpreted equivalently, that is as synonyms. Semantics often performs a sort of smoothing of the commands, by removing features that may be not relevant, before they are sent to the robot motion controller. The ability to cope with semantics is thus a key feature of a HRI language and the main focus of the framework described in this section. Standard computer languages tackle this issue using several constructs to define general equivalence classes among symbols.

The first free object, named *action*, defines primitive motions using simple concepts that can be easily used in a HRI language. The actions represent motion trends, i.e., an action represents simultaneously a set of paths that span the same bounded region of the workspace. These paths are equivalent in the sense that they drive the robot through the same region of the workspace.

Definition 1 (Free action). *Let k be a time index, q_0 the configuration of a robot where the action starts to be applied and $a(q_0)|_k$ the configuration at time k of a path generated by action a.*

A free action is defined by a triple $A \equiv (q_0, a, B_a)$ where B_a is a compact set and the initial condition of the action, q_0, verifies,

$$a(q_0)|_0 = q_0, \tag{4}$$

$$\exists_{\epsilon > \epsilon_{\min}} \; : \; \mathcal{B}(q_0, \epsilon) \subseteq B_a, \tag{4b}$$

with $\mathcal{B}(q_0, \epsilon)$ a ball of radius ϵ centered at q_0, and

$$\forall_{k \geq 0} \;\; a(q_0)|_k \in B_a. \tag{4c}$$

$\square$

Definition 1 creates an object, the action, able to inclose different paths with similar (in a wide sense) objectives. Paths that can be considered semantically equivalent, for instance because they lead to a successful execution of a mission, may be enclosed within a single action.

Representing the objects in Definition 1 in the form of a diagram it is possible to establish a correspondence between free actions and the sign model (3),

$$\begin{tikzcd}
q_0 & (q_0, a, B_a) \arrow[l, "semantics_Q"'] \arrow[r, "semantics_B"] \arrow[d, "synctatics"] & B_a \\
& A \arrow[ul, "pragmatics_Q"] \arrow[ur, "pragmatics_B"'] &
\end{tikzcd}$$

The a label represents the algorihm that generates the paths for the robot to follow. The projection maps $semantics_B$ and $semantics_Q$ express the fact that multiple paths starting in a neighborhood of q_0 and lying inside B_a may lead to identical results. The $pragmatics_B$ map expresses the fact that given the action being executed it may be possible to infer the corresponding bounding region. Similarly, $pragmatics_Q$ represents the maps that infer the initial condition q_0 given the action being executed. The *synctatics* map simply expresses the construction of an action through Definition 1.

Following model (3), different actions (with different a labels) can yield the same meaning, that is, the two actions can produce the same net effect in a mission. This amounts to require that the following diagram commutes,

$$\begin{tikzcd}
A \arrow[rrr, "equality"'] \arrow[d, shift right, "semantics_Q"'] \arrow[d, shift left, "semantics_B"] & & & A' \arrow[d, shift right, "semantics_{Q'}"'] \arrow[d, shift left, "semantics_{B'}"] \\
Q \times B_a & & & Q \times B_{a'} \arrow[lll, "\mathbf{1}_M"]
\end{tikzcd} \tag{5}$$

where $\mathbf{1}_M$ stands for the identity map in the space of meanings, M.

Diagram (5) provides a roadmap to define action equality as a key concept to evaluate sign semantics.

Definition 2 (Free action equality).

Two actions (a_1, B_{a_1}, q_{0_1}) *and* (a_2, B_{a_2}, q_{0_2}) *are equal, the relation being represented by* $a_1(q_{0_1}) = a_2(q_{0_2})$*, if and only if the following conditions hold*

$$a_1(q_{0_1}), a_2(q_{0_2}) \subset B_{a_1} \cap B_{a_2} \tag{6}$$

$$\forall_{k_2 \geq 0}, \exists_{k_1 \geq 0}, \exists_\epsilon \ : \ a_1(q_{0_1})|_{k_1} \in \mathcal{B}(a_2(q_{0_2})|_{k_2}, \epsilon) \subset B_{a_1} \cap B_{a_2} \tag{6b}$$

□

The realization for the free action of Definition 1 is given by the following proposition.

Proposition 1 (Action).

Let $a(q_0)$ *be a free action. The paths generated by* $a(q_0)$ *are solutions of a system in the following form,*

$$\dot{q} \in F_a(q) \tag{7}$$

where F_a *is a Lipschitzian set-valued map (see Appendix A) with closed convex values verifying,*

$$F_a(q) \subseteq T_{B_a}(q) \tag{7b}$$

where $T_{B_a}(q)$ *is the contingent cone to* B_a *at* q *(see Appendix B for the definition of this cone).*

□

The demonstration of this proposition is just a re-statement, in the context of this paper, of Theorem 5.6 in [26] on the existence of invariant sets for the inclusion (7).

■

The convexity of the values of the F_a map must be accounted for when specifying an action. The Lipschitz condition imposes bounds on the growing of the values of the F_a map. In practical applications this assumption can always be verified by proper choice of the map. This condition is related to the existence of solutions to (7), namely as it implies upper semi-continuity (see [26], Proposition 2.4).

Proposition 2 (Action identity). *Two actions* a_1 *and* a_2*, implemented as in Proposition 1, are said equal if,*

$$B_{a_1} = B_{a_2} \tag{8}$$

$$\exists_{k_0} \ : \ \forall_{k > k_0}, \ \ F_{a_1}(q(k)) = F_{a_2}(q(k)) \tag{8b}$$

□

The demonstration follows by direct verification of the properties in Definition 2.

By assumption, both actions verify the conditions in Proposition 1 and hence their generated paths are contained inside $B_{a_1} \cap B_{a_2}$ which implies that (6) is verified.

Condition (8b) states that there are always motion directions that are common to both actions. For example, if any of the actions a_1, a_2 generates paths restricted to $F_{a_1} \cap F_{a_2}$ then condition (6b) is verified. When any of the actions generates paths using motion directions outside $F_{a_1} \cap F_{a_2}$ then condition (8b) indicates that after time k_0 they will be generated after the same set of motion directions. Both actions generate paths contained inside their common bounding region and hence the generated paths verify (6b).

■

A sign system is defined by the signs and the morphisms among them. The action equality induces an equality morphism. Two additional morphisms complete the algebraic structure: action composition and action expansion.

Definition 3 (Free action composition). *Let $a_i(q_{0_i})$ and $a_j(q_{0_j})$ be two free actions. Given a compact set M, the composition $a_{j \circ i}(q_{0_i}) = a_j(q_{0_j}) \circ a_i(q_{0_i})$ verifies,*

$$\begin{aligned} &\textit{if } B_{a_i} \cap B_{a_j} \neq \emptyset \\ &\qquad a_{j\circ i}(q_{0_i}) \subset B_{a_i} \cup B_{a_j} && (9) \\ &\qquad B_{a_i} \cap B_{a_j} \supseteq M && (9b) \\ &\textit{otherwise, the composition is undefined.} \end{aligned}$$

□

Action $a_{j\circ i}(q_{0_i})$ resembles action $a_i(q_{0_i})$ up to the event marking the entrance of the paths into the region $M \subseteq B_{a_i} \cap B_{a_j}$. When the paths leave the common region M the composed action resembles $a_j(q_{0_j})$. While in M the composed action generates a link path that connects the two parts.

Whenever the composition is undefined the following operator can be used to provide additional space to one of the actions such that the overllaping region is non empty.

Definition 4 (Free action expansion). *Let $a_i(q_{0_i})$ and $a_j(q_{0_j})$ be two actions with initial conditions at q_{0_i} and q_{0_j} respectively. The expansion of action a_i by action a_j, denoted by $a_j(q_{0_j}) \boxtimes a_i(q_{0_i})$, verifies the following properties,*

$$B_{j\boxtimes i} = B_j \cup M \cup B_i, \quad \textit{with } M \supseteq B_i \cap B_j \tag{10}$$

where M is a compact set representing the expansion area and such that the following property holds

$$\exists_{q_{0_k} \in B_j} \; : \; a_i(q_{0_i}) = a_j(q_{0_k}) \tag{10b}$$

meaning that after having reached a neighborhood of q_{0_k}, $a_i(q_i)$ behaves like $a_j(q_j)$.

□

The use of M emphasizes the nature of the expansion region (alternatively, it can be included directly in B_{a_j}). M can be defined as the minimum amount of space that is required for the robot to perform any maneuver.

Proposition 3 (Action composition). *Let a_i and a_j be two actions defined by the inclusions*

$$\dot{q}_i \in F_i(q_i) \quad \textit{and} \quad \dot{q}_j \in F_j(q_j)$$

with initial conditions q_{0_i} and q_{0_j}, respectively. The action $a_{j\circ i}(q_{0_i})$ is generated by $\dot{q} \in F_{j\circ i}(q)$, with the map $F_{j\circ i}$ given by

$$F_{j\circ i} = \begin{cases} F_i(q_i) & \textit{if } q \ni B_i \backslash M \quad \textit{(3)} \\ F_i(q_i) \cap F_j(q_j) & \textit{if } q \in M \quad \textit{(3b)} \\ F_j(q_j) & \textit{if } q \in B_j \backslash M \quad \textit{(3c)} \\ \emptyset & \textit{if } B_i \cap B_j = \emptyset \quad \textit{(3d)} \end{cases}$$

for some $M \subset B_j \cap B_i$.

Outside M the values of F_i and F_j verify the conditions in Proposition 1. Whenever $q \in M$ then $F_i(q_i) \cap F_j(q_j) \subset T_{B_j}(q)$.

□

The first trunk of the resulting path, given by (3), corresponds to the path generated by action $a_i(q_{0_i})$ prior to the event that determines the composition. The second trunk, given by (3b), links the paths generated by each of the actions. Note that by imposing that $F_i(q_i) \cap F_j(q_j) \subset T_{B_j}(q_j)$ the link paths can move out of the region M. The third trunk, given by (3c), corresponds to the path generated by action $a_j(q_{0_j})$.

By Proposition 1, each of the trunks is guaranteed to generate a path inside the respective bounding region and hence the overall path verifies (9).

■

The action composition in Proposition 3 generates actions that resemble each individual action outside the overlapping region. Inside the overlapping area the link path is built from motion directions common to both actions being composed. The crossing of the boundary of M defines the events marking the transition between the trunks.

Whenever $F_i(q_i) \cap F_j(q_j) = \emptyset$ it is still possible to generate a link path, provided that M has enough space for maneuvering. The basic idea, presented in the following proposition, is to locally enlarge either $F_i(q_i)$ or $F_j(q_j)$. Iterative procedures can be used for this purpose (see [25] for details).

Proposition 4 (Action expansion).

Let a_i and a_j be two actions defined after the inclusions

$$\dot{q}_i \in F_i(q_i) \quad \textit{and} \quad \dot{q}_j \in F_j(q_j)$$

The expansion $a_{j\boxtimes i}(q_{0_i})$ verifies the following properties

$$F_{i\boxtimes j} = \begin{cases} F_i & \textit{if } q \ni B_i \backslash M \qquad (11) \\ F_j \cup F_i & \textit{if } q \in B_i \cap B_j \cup M \qquad (11b) \end{cases}$$

where $M \supseteq B_i \cap B_j$ is the expansion set chosen large enough such that $F_j \cup F_i$ verifies (7b).

□

Condition (11) generates paths corresponding to the action $a_i(q_{0_i})$. These paths last until an event, triggered by the crossing of the boundary of M, is detected. This crossing determines an event that expands the overall bounding region by M and the set of paths, by F_j, as expressed by (11b).

Assuming that $F_j \cup F_i \subset T_{B_i \cap B_j \cup M}$, that is, it verifies (7b), the complete path is entirely contained inside the expanded bounding region. After moving outside M paths behave as if generated by action a_i, as required by (10b).

■

Instead of computing a priori M, the expansion operator can be defined as a process by which action a_i converges to action a_j in the sense that $F_i(q_i) \rightarrow F_j(q_j)$ and M is the space spanned by this process.

Additional operators may be defined in the space of actions. For the purpose of the paper, i.e., defining the properties of a set of actions sufficient to design successful missions, action composition and expansion are the necessary and sufficient operators.

The overall architecture can be represented as shown in Figure 1. This architecture naturally yields a system of signs the robots can use to interact with each other much like a basic natural language. The components of this crude language are the elements forming the actions. The role of the supervisor is (i) to trigger the application of the composition and expansion operators whenever specific events are detected and, (ii) to manage the interaction with the external environment using this language, namely selecting bounding regions and initial conditions for the actions.

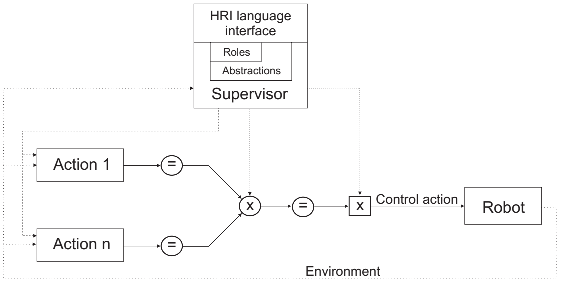

Fig. 1. The architecture for HRI

For the case of the composition operator the triggering events can be the crossing of some a priori defined region. The expansion operator is triggered when an event indicating that it is not possible to link the current action with the next chosen one is detected.

The supervisor block can be implemented as a finite state automaton. The states shape the actions bounding regions. The transitions can be identified with sequences of composition and expansion operations. For single robot missions each state basically sets a goal region for the robot to reach and shapes it to account for the external environment and mission. For team missions each state shapes the bounding regions using also the information from the other robots. Different automata yield different roles for the robot, each emphasizing specific skills, e.g., tracking moving people using sensor data, wandering, and systematically exploring the environment.

5 Experimental results

This section presents two basic simulation experiments on HRI. Both experiments illustrate the behavior of the system when the robots are moving towards a goal region. The experiments are extremely simple as the emphasis of the paper is not high level behavior design, which is related to the supervisor design. The experiments emphasize the visual quality (absence of complex maneuvering) of the trajectories obtained and the ability of the robots to move according motion trends instead of specific paths. The basic idea behind the experiments is that some external agent, human or robot, issues linguistic commands that lead the robot towards a goal region.

The setup considered can be compared to other described in the literature for HRI experiments. For instance, in [22] a robot is simply made to navigate around a standard environment, with static obstacles. In [2] a robot simply approaches a group of people wandering in the neighborhood as if joining them to take part in a conversation. In [12] robots are made to wander around in an exhibition scene, collecting and interpreting the sensor data to a human-comprehensible textual description. In [4] a robot is controlled using spatial references (e.g., go behind the table) to generate the adequate motion trend.

Unicycle robots, moving in a synthetic scenario, are considered in both experiments. The robots use a single action defined as

$$F(q) = (G - q) \cap H(q) \tag{11}$$

$$B(q) = \{p | p = q + \alpha G(q), \quad \alpha \in [0, 1]\} \tag{12}$$

where q is the configuration of the robot, G stands for the goal set, and $H(q)$ stands for the set of admissible motion directions at configuration q (easily obtained from the well known kinematics model of the unicycle). This action simply yields a motion direction pointing straight to the goal set from the current robot configuration. Often, the set of admissible motion directions that lead straight to the goal region is empty, $F(q) = \emptyset$, resulting in a singleton bounding region (the current configuration q) and no admissible control. In such cases the bounding region must be expanded using operator 4. The expansion action is simply given by

$$F_{i\boxtimes j} = \begin{cases} H_i(q) \cup \left\{ \begin{matrix}\text{set of motion} \\ \text{directions}\end{matrix} \mid d(H_i, G - q) \to 0 \right\} & \\ & \text{if} \;\; q \ni B_i \backslash M \\ & \\ F_i(q) & \text{otherwise} \end{cases}$$

where $d(,)$ stands for a distance between the sets in the arguments. This action corresponds to having $H(q)$ converging to $G - q$. For the presented experiments the algorithm chosen is described in [24]. The same set of actions and the supervisors is used by both robots.

The simulation environment is implemented as a multi-thread system. Each robot simulator thread runs at 10 Hz whereas the architecture thread runs at 1 Hz. Data is recorded by an independent thread at 10 Hz.

5.1 Mission 1

The first experiment demonstrates the operation of two robots operating isolatedly, trying to reach the same goal region. No information is exchanged between the robots and no obstacle avoidance behaviors were considered.

Figure 2 shows the trajectories followed by the robots superimposed on the synthetic image representing the test environment. The irregular shapes in the upper part of the images represent the region to be reached by the robots. The goal region is defined as a circle centered at the centroid of the convex hull of the countour of these shapes (basic image processing techniques were used). This circle is shown in light colour superimposed on the corresponding shape. The symbol $\circ$ marks the position of each robot along the mission. Marks connected by a dashed line were recorded at the same time.

Both robots start at the lower part of the image, with 0 rad orientation. This immediatelly forces the use of the expansion operator as the admissible motion directions lie outside the cone defined by $G - q_0$. Nevertheless, the trajectories obtained show a fairly acceptable behavior namely in the initialy stage where the basic sequence expansion-composition is constantly being triggered.

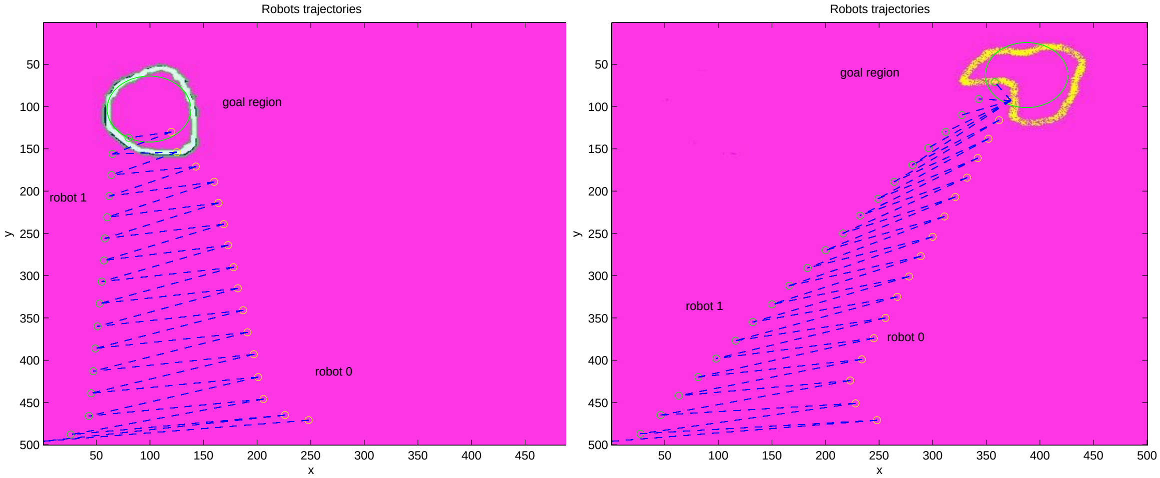

Fig. 2. Independent robots - Two runs

5.2 Mission 2

The proposed mission is classical in the context of robotics experiments. The two robots must move in a loose formation towards a common goal region while avoiding direct contact which each other. Maintaining such a formation requires the loose form of interaction between the robots that is easily modeled with the framework developed.

Figure 3 illustrates two runs of this mission. The supervisor at each robot shapes the action bounding regions to avoid contact between the robots. A basic shaping procedure is considered. The action bounding region of each robot is obtained by removing any points bellonging also to that of the teammate. This results in a much smaller bounding region that constrains significantly the trajectories the action generates.

While interacting with the teammate, each robot replaces the original mission goal by intermediate goal regions placed inside the shaped bounding regions. Once an intermediate goal is reached the robot stops whereas the teammate continues towards the original mission goal (as it does not need to shape its own action bounding region).

Figure 4 illustrates an alternative shaping of the action bounding region used when an obstacle is present in the environment. In this case an intermediate goal region is chosen far from the obstacle such that the new action bounding region allows the robots to move around the obstacle. This strategy has close connections to well known path planning schemes widely used in robotics.

Robot 0 is the first to reach the intermediate goal and proceeds to the final goal. In the leftmost plot the interaction between the robots leads to trajectories passing far from the obstacle. In the righmost plot, the bounding regions of robot 0 are not influenced by the obstacle at the beginning of the mission and hence the robot tends to approach the obstacle (without colliding - robots where not given physical dimensions). Meanwhile, the interaction with robot 1 is clearly visible as the trajectory passes far from the obstacle and robot 0. The slight oscilations in the initial stage, clearly visbible in robot 1, is due to the interaction between the robots through the shaping of the action bounding regions.

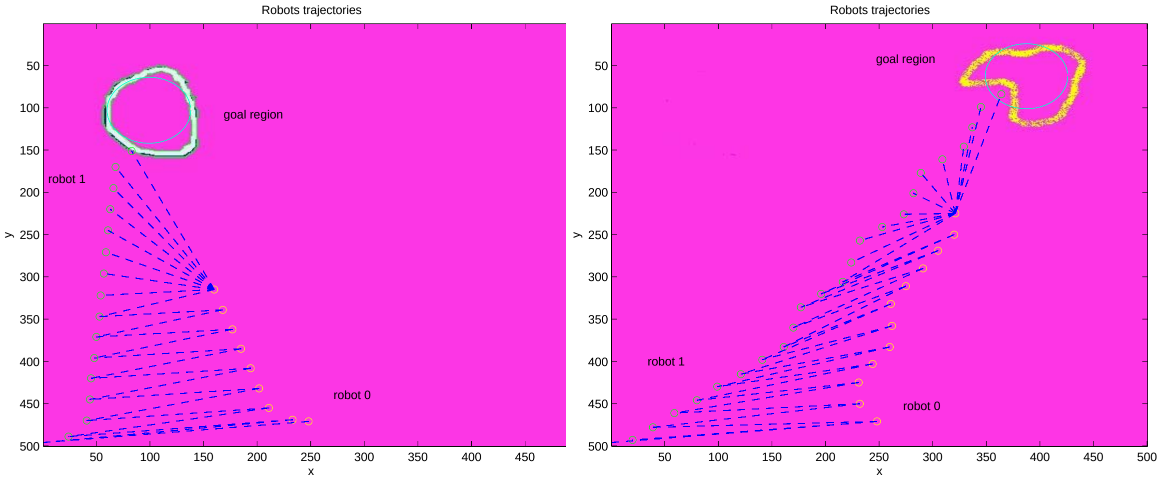

Fig. 3. Interacting robots - Two runs

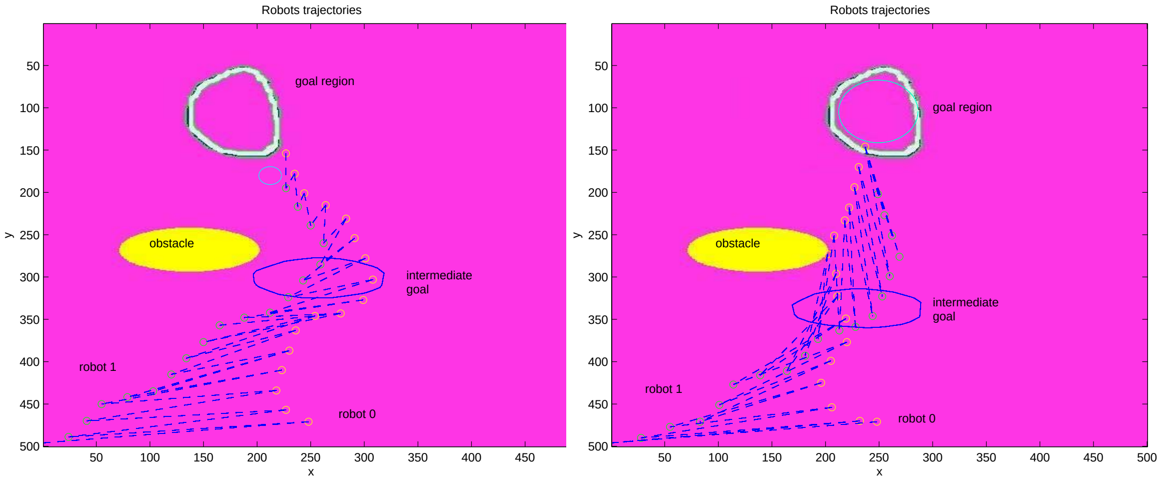

Fig. 4. Interacting robots in the presence of a static obstacle

6 Conclusions

The paper presented an algebraic structure to model HRI supported on semiotics principles. The key feature of this work is that is handles in a unified way any interaction between a robot and its external environment. Furthermore, the basic data units exchanged among the robots have straighforward meanings.

Although extremely simple, the simulation experiments presented capture a key feature of linguistic interactions, both among robots and between robots and humans. Namely, the motion is specified according to a motion trend, instead of a rigid path. The results illustrate acceptable trajectories both for single and team missions. The initial configurations do not promote straight line motion. Nevertheless, no harsh maneuvering is observed.

Future work includes (i) analytical study of controllability properties in the framework of hybrid systems with the continuous state dynamics given by differential inclusions and, (ii) the study of the intrinsic properties for the supervisor building block, currently implemented as a finite state automata, that may simplify design procedures.

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A Lipschitz set-valued maps

A set-valued map F is said to be Lipschitz if it verifies.

$$\exists_{\epsilon \geq 0} \ : \ \forall_{x_1, x_2 \in X}, \ F(x_1) \subset F(x_2) + \epsilon |x_1 - x_2|_X \mathcal{B}_Y \tag{13}$$

where

$$\mathcal{B}_Y = \{ y \in Y \ : \ |y| \leq 1 \} \tag{14}$$

where $|\cdot|_X$ stands for a norm in X.

B Contingent cones

Nonsmooth analysis uses tangency concepts for which a variety of contingent cones is defined (see for instance [26]).

The contingent cone used in the paper is defined as

$$T_B(q) = \left\{ v \ : \ \lim_{h \to 0+} \inf \frac{d_B(q + hv)}{h} = 0 \right\} \tag{15}$$

where

$$d_B(q) = \inf_{p \in B} |p - q|_Q \tag{16}$$

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