SEMIOTICS AND HUMAN-ROBOT INTERACTION

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Abstract: This paper describes a robot control architecture supported on a human-robot interaction model obtained directly from semiotics concepts.
The architecture is composed of a set of objects defined after a semiotic sign model. Simulation experiments using unicycle robots are presented that illustrate the interactions within a team of robots equipped with skills similar to those used in human-robot interactions.

1 INTRODUCTION

This paper describes part of an ongoing project aiming at developing new methodologies for semi-autonomous robot control that, in some sense, mimic those used by humans in their relationships. The paper focus (i) in the use of semiotic signs to control robot motion and (ii) their use in the interaction with humans. The approach followed defines (i) a set of objects that capture key features in human-robot and robot-robot interactions and (ii) an algebraic system with operators to work on this space of the objects.

In a wide variety of applications of robots, such as surveillance in wide open areas, rescue missions in catastrophe scenarios, and working as personal assistants, the interactions among robots and humans are a key factor in the success of a mission. In such missions contingency situations may lead a robot to request external help, often from a human operator, and hence it seems natural to search for interaction languages that can be used by both. Furthermore, a unified framework avoids the development of separate competences to handle human-robot and robot-robot interactions.

The numerous robot control architectures proposed in the literature account for human-robot interactions (HRI) either explicitely through interfaces to handle external commands, or implicitely, through task decomposition schemes that map high level mission goals into motion commands. Examples of current architectures developed under such principles can be found in (Aylett and Barnes, 1998),(Huntsberger et al., 2003),(Albus, 1987),(Kortenkamp et al., 1999). If the humans are assumed to have enough knowledge on the robots and the environment, imperative computer languages can be used for HRI, easily leading to complex communication schemes. Otherwise, declarative, context dependent, languages, like Haskell, (Peterson et al., 1999) and FROB, (Hager and Peterson, 1999), have been proposed to simulate robot systems and also as a mean to interact with them. BOBJ was used in (Goguen, 2003) to illustrate examples on human-computer interfacing. RoboML, (Makatchev and Tso, 2000), supported on XML, is an example of a language explicitly designed for HRI, accounting for low complexity programming, communications and knowledge representation. In (Nicolescu and Matarić, 2001) the robots are equipped with behaviors that convey information on their intentions to the outside environment. These behaviors represent a form of implicit communication between agents such as the robot following a human without having been told explicitly to do so. This form of communication, without explicit exchange of data is an example of interaction that can be modeled using semiotics.

Semiotics studies the interactions among humans. These are often characterized by the loose specification of objectives for instance as when a sentence expresses an intention of motion instead of a specific path. Capturing some of these features, typical of natural languages, is the aim of this project.

The paper is organised as follows. Section 2

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presents key concepts in semiotics to model human-human interactions and motivates their use to model human-robot interactions. These concepts are used in Section 3 to define the building blocks of the proposed architecture. Section 4 presents a set of basic experiments that demonstrate the use of the semiotic model developed along the paper. Section 5 presents the conclusions and future work.

2 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 commonly programmed to follow trajectories, hence operating at a low level of abstraction.

Semiotics is a branch of general philosophy which studies the interactions among humans, such as the linguistic ones (see (Chandler, 2003) for an introduction to semiotics) and hence it is a natural framework where to search for new methodologies to model human-robot interactions. In addition, this should be extended to robot-robot interactions yielding a unifying framework to handle any interaction between a robot and the external environment.

An algebraic formulation for semiotics and its use in interface design has been presented in (Malcolm and Goguen, 1998). An application of hypertext theory to world wide web was developed in (Neumüller, 2000) Machine-machine and human-human interactions over electronic media (such as the Web) have been addressed in (Codognet, 2002). Semiotics has been use in intelligent control as the term encompassing the main functions related to knowledge, namely acquisition, representation, interpretation, transformation and manipulation (see for instance (Meystel and Albus, 2002)) and often directly related to the symbol grounding concept of artificial intelligence.

The idea underlying semiotics is that humans communicate among each other (and with the environment) through signs. 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 (Malcolm and Goguen, 1998) for a definition of sign system) and hence, under reasonable assumptions on the existence of identity maps, map composition, and composition association, can be modeled using category theory framework. The following diagram, suggested by the "semiotic triangle" diagram common in the literature on this area (see for instance (Chandler, 2003)), expresses the relations between the three components of a sign.

$$\begin{tikzcd}
& M \arrow[dr, "pragmatics^\star"] & \\
L \arrow[ur, "semantics"] \arrow[rr, dashed, shift left, "syntactics"] & & O \arrow[ll, dashed, shift left, "syntactics^\star"] \arrow[dl, "pragmatics"] \\
& M \arrow[ul, "semantics^\star"] &
\end{tikzcd} \tag{1}$$

Labels, (L), represent the vehicle through which the sign is used. 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 (1) represent the different perspectives used in the study of signs. Semiotics currently considers three different perspectives: semantics, pragmatics and syntactics, (Neumüller, 2000). Semantics deals with the general relations among the signs. For instance, it defines whether or not a sign can have multiple meanings. In human-human interactions amounts to say that different language constructs can be interpreted equivalently, that is as synonyms. 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 (as the "semiotic triangle" is usually represented as an undirected graph).

3 AN ARCHITECTURE FOR HRI

This section introduces the architecture by first defining a set of context free objects and operators on this set that are compatible (in the sense that they can be identified) with diagram (1). Next, the corresponding realizations for the free objects are described. 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 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.

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,

$$q_0 \in B_a, \tag{2}$$
$$a(q_0)|_0 = q_0, \tag{2b}$$
$$\exists_{\epsilon > \epsilon_{\min}} \ : \ \mathcal{B}(q_0, \epsilon) \subseteq B_a, \tag{2c}$$

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

$$\forall_{k \geq 0} \ \ a(q_0)|_k \in B_a. \tag{2d}$$

□

Actions are 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 signs verifying model (1),

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

The projection maps $semantics_B$ and $semantics_Q$ express the fact that multiple trajectories 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 a bounding region it may be possible to infer the action being executed. Similarly, $pragmatics_Q$ represents the maps that infer the action being executed given the initial condition q_0. The $synctatics$ map simply expresses the construction of an action through Definition 1.

Following model (1), different actions 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,

$$\begin{tikzcd}
A \arrow[r, "equality"'] \arrow[d, "semantics_B"] & A' \arrow[d, "semantics_{B'}"] \\
B_a & B_{a'} \arrow[l, "\mathbf{1}_M"]
\end{tikzcd} \tag{3}$$

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

Diagram (3) 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*

$$a_1(q_{0_1}), a_2(q_{0_2}) \subset B_{a_1} \cap B_{a_2} \tag{4}$$

$$\forall_{k_2 \geq 0}, \exists_{k_1 \geq 0}, \exists_\epsilon \ : \\ a_1(q_{0_1})|_{k_1} \in \ \mathcal{B}(a_2(q_{0_2})|_{k_2}, \epsilon) \subset B_{a_1} \cap B_{a_2} \tag{4b}$$

□

Expressions (4) and (4b) define the $equality$ map in diagram (3). It suffices to choose identical bounding regions (after condition (4)) and a goal region inside the bounding regions (after condition (4b)) to where the paths generated by both actions converge.

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,*

$$\dot{q} \in F_a(q) \tag{5}$$

where F_a is a Lipschitzian set-valued map with closed convex values verifying,

$$F_a(q) \subseteq T_{B_a}(q) \tag{5b}$$

where $T_{B_a}(q)$ is the contingent cone to B_a at q (see (Smirnov, 2002) for the definition of this cone).

□

The demonstration of this proposition is just a restatement, in the context of this paper, of Theorem 5.6 in (Smirnov, 2002) on the existence of invariant sets for the inclusion (5).

■

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 (5), namely as it implies upper semi-continuity (see (Smirnov, 2002), Proposition 2.4).

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

$$B_{a_1} = B_{a_2} \tag{6}$$
$$\exists_{k_0} \ : \ \forall_{k > k_0}, \ \ F_{a_1}(q(k)) = F_{a_2}(q(k)) \tag{6b}$$

□

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 (4) is verified.

Condition (6b) 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 (4b) is verified. When any of the actions generates paths using motion directions outside $F_{a_1} \cap F_{a_2}$ then condition (6b) 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 (4b).

■

A sign system is defined by the signs and the morphisms among them. In addition to the equality map, two other morphisms are defined: 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,*

if $B_{a_i} \cap B_{a_j} \neq \emptyset$

$$a_{j\circ i}(q_{0_i}) \subset B_{a_i} \cup B_{a_j} \quad (7)$$

$$B_{a_i} \cap B_{a_j} \supseteq M \quad (7b)$$

otherwise, the composition is undefined.

□

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 overlapping 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,*

$$B_{j\boxtimes i} = B_j \cup B_i, \ \textit{ with } B_i \cap B_j \subseteq M \quad (8)$$

where M is a compact set representing the minimal amount of space required for the robot to maneuver and such that the following property holds

$$\exists_{q_{0_k} \in B_j} \ : \ a_i(q_{0_i}) = a_j(q_{0_k}) \quad (8b)$$

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

□

Given the realization (1) chosen for the actions, the composition and expansion operators can be realized through the following propositions.

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

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

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 (7).

■

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 $F_j(q_j)$.

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

$$F_{i\boxtimes j} = \begin{cases} F_i & \text{if } q \ni B_i \backslash M \quad (9) \\ F_j \cup F_i & \text{if } q \in B_i \cap B_j \cup M \quad (9b) \end{cases}$$

where $M \supseteq B_i \cap B_j$ is the expansion set chosen large enough such that $F_j \cup F_i$ verifies (5b).

□

Condition (9) 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 (9b).

Assuming that $F_j \cup F_i \subset T_{B_i \cap B_j \cup M}$, that is, it verifies (5b), the complete path is entirely contained inside the expanded bounding region. After moving outside M paths behave as of generated by action a_i, as required by (8b).

■

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.

The objects and operators defined above are combined in the following diagram,

$$\begin{tikzcd}
 & A_\circ \arrow[r, "="'] & A \arrow[d, "\circ"] & \\
A \arrow[r, "="'] & A \arrow[u, "s_\circ"] \arrow[d, "s_\boxtimes"'] & A \arrow[r, "="'] & A \\
 & A_\boxtimes \arrow[r, "="'] & A \arrow[u, "\boxtimes"'] &
\end{tikzcd} \quad (9)$$

where A stands for the set of actions available to the robot, $A_\circ$ and $A_\boxtimes$ stand for the sets of actions representing primitive motions used in composition and expansion, respectively.

The product like part (in the lefthand part) of diagram (9) represents the supervision strategy that determines which of the action sets, $A_\circ$ or $A_\boxtimes$, is selected at each event. This strategy is mission dependent and is detailed in the $s_\circ$ and $s_\boxtimes$ maps.

4 EXPERIMENTAL RESULTS

This section presents two basic simulation experiments using a team of three unicycle robots and an experiment with a single real unicycle robot.

Missions are specified through goal regions the robots have to reach. This resembles a typical human-robot interaction, with the human specifying a motion trend the robot has to follow through the goal region. Furthermore, intuitive bounding regions are easily constructed from them. The human operator is thus not explicitely present in the experiments. Nevertheless, as results clear from the third experiment (with the real robot) there is no lack of generality.

Interactions among the teammates are made through the action bounding regions, that is each robot has access to the bounding region being used by any teammate.

The robots use a single action, denoted $a_\circ$, defined as

$$a_\circ = \begin{cases} F(q) = (G - q) \cap H(q) \\ B(q) = \{p | p = q + \alpha G(q), \quad \alpha \in [0, 1]\} \end{cases} \quad (10)$$

where q is the configuration of the robot, G stands for a 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. Whenever there are no admissible controls, i.e., the set of admissible motion directions that lead straight to the goal region is empty, $F(q) = \emptyset$, the bounding region is expanded using the action

$$a_\boxtimes = \begin{cases} H_i(q) \cup \left\{ \begin{array}{c}\text{set of motion} \\ \text{directions}\end{array} \mid d(H_i, G - q) \rightarrow 0 \right\} & \\ & \text{if } q \ni B_i \backslash M \\ F_i(q) & \text{otherwise} \end{cases}$$

where $d(,)$ stands for a distance between the sets in the arguments. This action corresponds to having $H(q)$ converging to $G - q$. Generic algorithms already described in the literature can be used obtain this sort of convergence. The same set of actions and the supervisor maps is used by all the robots.

In the simulation experiments robots have access to a synthetic image representing a top view of the environment and start their mission at the lower part of the image. The irregular shape in the upper part of the images shown in the following sections represents the raw mission goal region to be reached by the robots. Basic image processing techniques are used to extract a circle goal region, centered at the centroid of the convex hull of the countour of these shapes. This circle is shown in light colour superimposed on the corresponding shape. The simulations were implemented as a multi-thread system. Each robot simulator thread runs at an average 100 Hz whereas the architecture thread runs at an average 80 Hz. Experiments data is recorded by an independent thread at 100 Hz.

In the real experiment, the image data is used only to extract a goal region for the robot to reach. The navigation relies on odometry data.

4.1 Mission 1

The purpose of this experiment is to assess the behavior of the team when each robot operates isolatedly. Each robot tries to reach the same goal region (in the upper righthand side of the image). No information is exchanged between the teammates and no obstacle avoidance behaviors are considered. In the simulation experiments robots 1 and 2 start with a 0 rad orientation whereas robot 0 starts with π rad orientation.

Figure 1 shows the trajectories generated by the robots. The symbol $\circ$ marks the position of each robot along the mission. Dashed lines connect the time related robot position marks.

The supervisor maps were chosen as,

$$\begin{array}{lll} s_\circ \equiv a_\circ & \text{if} & H(q) \cap G - q \neq \emptyset \\ s_\boxtimes \equiv a_\boxtimes & \text{if} & H(q) \cap G - q = \emptyset \end{array} \tag{11}$$

The oscilations in all the trajectories in Figure 1 result from the algorithm used to expand the action bounding region at the initial time as the initial configuration of any of the robots does not point straight to the goal set.

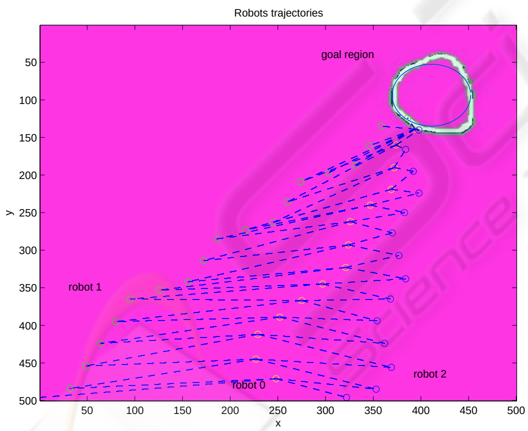

Figure 1: Independent robots.

4.2 Mission 2

The robots have no physical dimensions but close positions are to be avoided during the travel. This condition is relaxed as soon as the robot reaches the goal set, that is, once a robot reaches the goal region and stops the others will continue trying to reach the goal independently of the distance between them.

The supervisor maps are identical to the previous mission. However, the co-domain of $s_\circ$, the set $A_\circ$, is changed to account for the interactions among the robots.

$$A^i_\circ = \begin{cases} F^i(q^i) = \left(G^i - q^i\right) \cap H^i(q^i) \\ B^i(q^i) \backslash \cup_{j \neq i} B^j(q^j) \end{cases} \tag{12}$$

where the superscript indicates the robot the action belongs to.

Actions in (12) use a subset of the motion directions in (10). The bounding region is constructed from that in (10) including the information from the motion trend of the teammates by removing any points belonging also to that of the teammates. The original mission goal is replaced by intermediate goal regions, G^i, placed inside the new bounding region. As the robots progress towards these intermediate goals they also approach the original mission goal. A potential drawback of this simple strategy is that the smaller bounding region constrains significatively the trajectories generated.

Figure 2 illustrates the behavior of the team when the robots interact using the actions (12). The global pattern of the trajectories shown is that of a line formation. Once the robots approach the goal region the distance between them is allowed to decrease so that each of them can reach the goal.

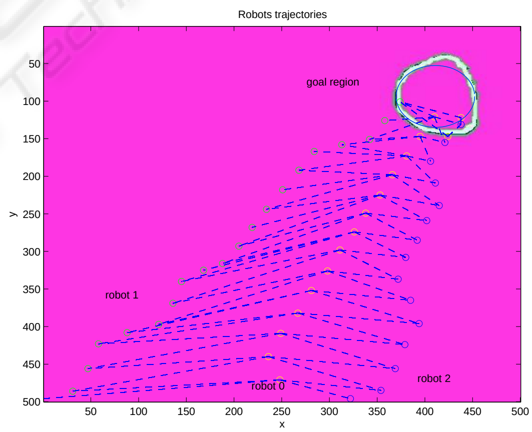

Figure 2: Interacting robots.

Figure 3 illustrates the behavior of the team when a static obstacle is present in the environment. Similarly to common path planning schemes used in robotics, 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.

From the beginning of the mission robots 0 and 1 find the obstacle in their way to the goal region and select the intermediate goal shown in the figure. After the initial stage where the robots use the expansion action aiming at aligning their trajectories with the direction of the goal. The interaction that results from the exchange of bounding regions is visible similarly as in the previous experiment. Robot 2 is not constrained by the obstacle and proceeds straight to the goal. Its influence in the trajectories of the teammates around the intermediate goal region is visible in the long dash lines connecting its position with those of the teammates.

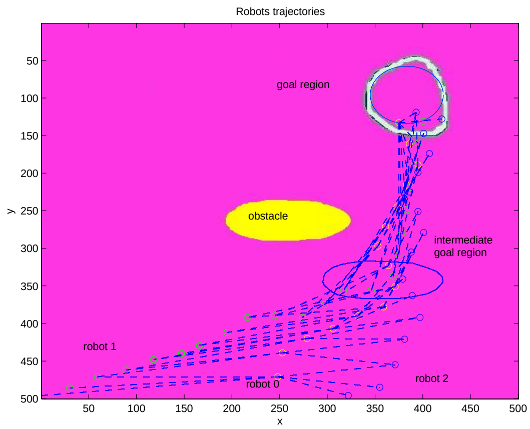

Figure 3: Interacting robots in the presence of a static obstacle.

4.3 Mission 3

This experiment, with a single robot, aims at validating the assessment of the framework done, in simulation, in Sections 4.1 and 4.2. The supervisor maps are those in (11).

Figure 4 shows the Scout robot and the goal region as extracted using basic color segmentation procedures. No obstacles were considered in this experiment.

The corresponding trajectory in the workspace is shown in Figure 5. The robot starts the mission with orientation $\pi/2$, facing the goal region, and hence maneuvering is not required. The robot proceeds directly towards the goal region. Figure 6 displays the trajectory when the robot is made to wander around the environment. Goal regions are defined at random instants and when detected by the robot its behavior changes to the goal region pursuing. The plot shows the positions of the robot when the targets were detected and when they are reached (within a 5cm error distance). The visual quality of these trajectories is close to those obtained in simulation which in a sense validates the simulations.

Figure 4: A goal region defined over an object in a laboratory scenario.

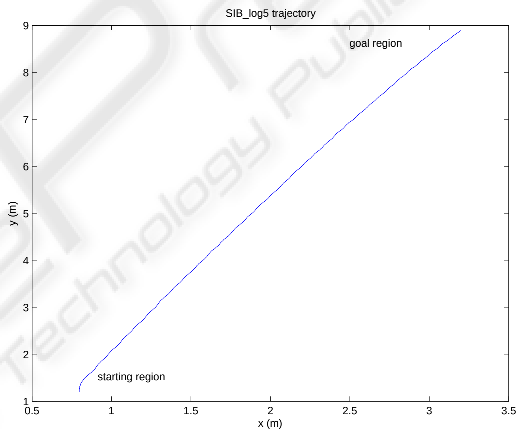

Figure 5: Moving towards a goal region.

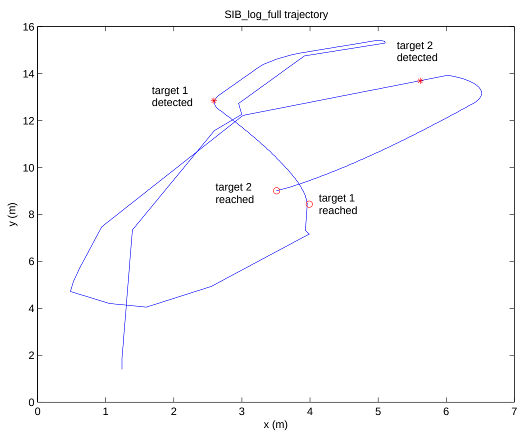

Figure 6: Moving betwen multiple goals regions.

5 CONCLUSIONS

The paper presented an algebraic framework to model HRI supported on semiotics principles. The framework handles in a unified way any interaction related to locomotion between a robot and its external environment.

The resulting architecture (see Figure 9) has close connections with multiple other proposals in the literature, namely in that a low level control layer and a supervision layer can be easily identified.

Although the initial configurations do not promote straight line motion, the simulation experiments presented show trajectories without any harsh maneuvering. The experiment with the real robot validates the simulation results in the sense that in both situations identical actions are used and the trajectories obtained show similar visual quality.

Future work includes (i) analytical study of controllability properties in the framework of hybrid systems with the continuous state dynamics given by differential inclusions, (ii) the study of the intrinsic properties for the supervisor building block, currently implemented as a finite state automata, that may simplify design procedures, and (iii) the development of a basic form of natural language for interaction with robots given the intuitive meanings that can be given to the objects in the framework.

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