MARKER-AUGMENTED ROBOT-ENVIRONMENT INTERACTION

Amol Dattatraya Mali
Electrical Engg. & Computer Science
University of Wisconsin, Milwaukee, WI 53211
mali@miller.cs.uwm.edu

Abstract

There has been an increasing interest in developing computational theories of autonomous robots. However the previous work has focused on intelligent modifications to internal computational structure of a robot, ignoring modifications to external environments. Our work is the first to formalize the modification of an environment by an introduction of markers that replace the internal state. Replacing internal state by addition of markers increases communication through the world. Use of markers has been shown to improve the effectiveness of robots at AAAI robot competitions and RoboCup competitions. We report on the semantics of markers using their logical description and the internal state they replace. We introduce several properties of markers and marker sets like redundancy, mutual exclusivity and efficiency. We show how the stimuli of behaviors can be modified when markers are introduced to replace internal state. We also report on a semi-automatic algorithm that allows robots to place markers in their world. We show how the algorithm can be extended for obtaining a higher replacement of internal state and for handling an autonomous removal of markers. We provide several guidelines for effectively introducing markers in a robot's world.

Key Words: Markers, Behaviors, Robots, Autonomy, Internal state

1. Introduction

The paradigms of autonomous robotic intelligence are moving towards a more distributed architecture. In this paper, we focus on the behavior-based robots that are typically reactive (though they may have a meta-level reasoner or a monitor), treating the world as an external memory from which knowledge can be retrieved by perception. Behavior-based systems became popular in robotics with the work of Brooks [1], who challenged the deliberative paradigm in AI by building stimulus-response based robots, also known as behavior-based robots. A typical behavior-based robot is a collection of several independent task-achieving modules with a simple distributed control mechanism. Each behavior mediates directly with the external world and the behaviors are in a parallel control structure, as opposed to the traditional serial structure where interaction with the world is processed serially through sensors, reasoners, planners, actuators, etc. All behavior-based systems attempt to reduce or eliminate the centralized shared memory, relying instead on parameter passing and communication between individual behaviors. Interesting results have been achieved using this strategy in the can collection task [2], drum sampling [3], a reactive serpentine robot that navigates complex pipe structures to inspect them [4], and a robot that reacts to bumps and slips while maintaining body posture [5].

Early research on robots assumed environment to be completely static, predictable and avoided sensory processes, e.g. in the first robot project [6], Shakey executed simplified plans with full a priori knowledge of the types of blocks it manipulated. The building and maintenance of and reasoning with global internal representations was considered to be responsible for the failure of this approach in more complex and dynamic environments. Ideas of Brooks [7] lead researchers to build robots without global representations. Robots in such systems communicate though the world by making changes to it that other robots can perceive.

Since some reactive robots exhibited problems like deadlocks and myopic behaviors, hybrid architectures with deliberative components to fix these began to be explored. In this transition, the potential of reactivity went largely unexamined. Making a system more reactive may involve replacing internal state by an external state that can be extracted through perception. Some internal states have to be updated whenever external world changes and replacing internal state by external cues eliminates such updates, since the most recent information is available in the world itself. Hence there are reasons for robots to be more reactive.

Kirsh [8] correctly points out that AI theorists have dwelled on intelligent use of time, hardly considering space. It is common to introduce markers to replace internal state to enhance the robot-environment interaction, e.g. entries in the mobile robot competitions of the American Association of Artificial Intelligence and the international Robocup competition. The rocks in the event of finding life on Mars [9] were painted black to aid in visual recognition. Black paper indicating the danger zones was spread out on a part of the floor. The doors of the lander were painted blue and orange. The life forms consisted of balls and cubes of bright colors. The event of finding the remote [10] which consisted of fetching a known set of objects used textureless surfaces to keep the object on and the objects were guaranteed to be well separated from one another. This approach simplified the visual problem of segmentation (determining which image region corresponds to which object) and thus the shape recognition algorithms did not have to worry about occlusion. The object detection mechanism in robotic soccer competition [11] was kept as simple as possible. Different objects had well defined colors that were used as a major cue in object detection. Since a single color or patch was not sufficient to provide orientation information, additional pink patch was added on the top of each robot. The ball was orange and the field was green and the markings on the side were white. Robots' tops were colored either blue or yellow to distinguish the team that they belonged to. The squiggle balls and the tennis balls in the "clean up the tennis court" event were painted black [12]. The vision system that was trained to recognize the yellow tennis balls and pink squiggle balls proved to be extremely reliable during the competition, benefitting from the color cues provided by the objects [13]. In the tennis ball collection event, the gate was marked by two cyan markers that were taped to the ground in front of the gate [13]. The goal area in the "clean up tennis court" event [14] was marked with a blue square. The rules of the middle-size autonomous robotic soccer [15] require that different objects have distinct colors: The field is green with white lines, goals are blue and yellow, and robots are black with light blue or magenta markers, depending on the team they play for. These stringent rules allow for simple mechanisms for object detection and recognition [15]. The following is a quote from [16]: "We added markers around the field to aid robot localization. We used 6 rectangular markers with color patches of size 29.7 cm × 21 cm. Two of these patches are placed on the top of each other. One is always magenta. The other is white for markers placed in the middle of the long field side. It is yellow or sky-blue for markers placed at the corners. Markers on the left side of the field (when facing the yellow goal) have magenta as upper color. For the right field side, magenta is below the other color". The following is quoted from [17]: “In the Robocup small-size (F180) league, five robots on each team play soccer on a green field marked with white lines. The ball is orange and the robots, as well as the goals, are marked either yellow or blue. In addition to the yellow or blue team marker (a ping-pong ball centered on the top of the robot), further markers are allowed as long as they have different colors. All colors are allowed for markers, as long as they are different from the reserved ones, and also the number and form of the markers changes from team to team. The vision system must be able to adapt quickly to the different markers of the opponents. The markers need to be designed carefully. Specifically, no combination of the markers from two different robots should be seen as a robot”. AAAI-2002 mobile robot host contest allowed markers if they were unobtrusive. Atlanta Hobby Robot Club holds a robot vaccum cleaning contest every year [18]. In the contest in 2002, the floor lamp, chair and box were centered over orange markers. These 3 objects were obstacles and robots were penalized if they pushed these objects off of their markers. Here are some of the RoboCup laws for middle-size robot league [19]: “A robot must have markings in order to be recognized by other robots and to be distinguished by the referee. Each robot must carry both color markers and number markers. Robots not carrying both markers are not eligible to play. Avoid using shiny material for robot surfaces. The league committee may exclude robots that do not conform to this rule. Base color of robot’s body must be black. Furthermore, color must be matte in order to minimize reflectivity. Every team is expected to try hard to hide non-black parts of the robot as much as possible, especially parts that have colors used for the ball or the field of play.”

The introduction of markers has been viewed more as a low-level fix rather than as a paradigm that deserves a separate investigation. Our work bridges this gap by formalizing the replacement of internal state via the introduction of markers. Though Brooks advocated using external world as its own model, he did not suggest the placement of markers to replace internal state. So the behavior-based agency in our work differs from Brooks' behavior-based agency since we allow an introduction of markers. Note that introduction of markers does not always fully eliminate internal models. The introduction of markers generally introduces simpler internal models. For example, a blue ball kept on a table helps in eliminating the internal model of the table. The blue ball serves as a marker kept on the table. The model of blue ball then needs to be internally stored, instead of the complex model of the table.

This paper makes the following contributions.

- We formalize the role of markers in replacing internal state. This makes further progress in this area possible, including algorithms for automatically placing and removing markers.

- We introduce the notions of efficiency of markers, redundancy and their mutual exclusivity. These metrics and properties are useful in correctly and efficiently placing markers.

- We show how behaviors' stimuli should be modified when markers are introduced to replace internal state.

- We report on an algorithm for an autonomous robotic placement of markers. We discuss possible extensions of this algorithm.

- We report on guidelines for correctly and efficiently placing markers.

This paper is organized as follows. We formalize reactive behaviors and markers in section 2. We define some metrics to evaluate markers in section 3. We also identify some criteria for a correct placement of markers in this section. We report on an algorithm for autonomous robotic placement of markers in section 4. We discuss some possible extensions of the autonomous-marker-placement algorithm in section 5. We also report on guidelines to correctly and efficiently place markers in this section. We present a case study to illustrate the use of markers in section 6. Our conclusions are presented in section 7.

2. A Model of Behaviors & Markers

In this section, we develop a formal model of behaviors and replacement of internal state via the introduction of markers.

$\Rightarrow$ denotes logical implication. $\wedge$ denotes logical AND. $\neg$ denotes negation. $\vee$ denotes logical OR. A pure conjunction of predicates or propositions can be considered as a set. Then subtraction, union and intersection operations over sets can be applied to the conjunctions. One can then also check if one conjunction is a subset of another. For example, $(a \wedge b \wedge c)$ can be considered as $\{a, b, c\}$. Then the result of $(a \wedge b \wedge c) - (c \wedge d \wedge f)$ is $(a \wedge b)$.

- **Behavior** - A behavior β_i is modeled as a 2 tuple $< s_i, c_i >$ and defined as a mapping from stimulus s_i to consequence c_i. A behavior is same as an atomic behavior. All variables in the predicates in the stimuli of behaviors are assumed to be existentially quantified.

- **Behavior space** - It is the set of all atomic behaviors of a robot. It is denoted by B and $\mid B \mid$ is size of the behavior space. Sequential or concurrent operation of atomic behaviors gives rise to a more complex behavior. Such complex behaviors are not included in the behavior space.

- **Stimulus** - It is assumed that stimuli of all behaviors are expressed as a pure conjunction of predicates, with the exception of the *local replacement of internal state* that we discuss later in this section. Universal truths which are required for the execution of a behavior are not listed in its stimulus, since such a list can be arbitrarily long. The universe is a conjunction of predicates denoted by U. Hence when we say that a stimulus is s_i, we mean that it is $(s_i \bigwedge X)$, where $(U \Rightarrow X)$, X being a part of the universe, e.g. to pick up a can, it is necessary for a robot to have a gripper that is not fixed to a table, but this is not listed in stimulus of the behavior *pick_up_can*. The stimulus s_i is defined to be logically at least as strong as stimulus s_x if $(s_i \Rightarrow s_x)$. It is stronger if $(s_i \Rightarrow s_x)$ is a tautology and s_x does not subsume s_i. For example, the stimulus $(a \wedge b \wedge c)$ is stronger than the following six stimuli $(a \wedge b), (b \wedge c)$, $(a \wedge c), a, b, c$.

- **Consequence** - It is assumed that the consequences of all behaviors are expressed as a pure conjunction of predicates. A consequence c_i is defined to be logically at least as strong as consequence c_j if $(c_i \Rightarrow c_j)$.

- **Marker** - The term marker is used in this paper to refer to (a) objects introduced in an environment or (b) new features added to current objects in an environment, with the intention of replacing internal state. Assume that a robot is supposed to collect all dishes and keep them in sink, except those on a table. One way to do this is to store a model of the table in the form of internal state and design *pick_up* behavior of the robot not to pick up dishes from the table. However one can put a dark blue cube at center of the table and replace the internal model of the table needed to evaluate $Table(x)$ in the stimulus of the behavior by the presence of the dark blue cube that can be sensed by vision. The dark blue cube is a marker.

A marker is a percept denoted by m_{ij} and is described by a pure conjunction of its features. m_{ij} denotes j th marker of i th type. Z denotes the number of types of markers. $t(f)$ denotes the time needed to determine that the logical sentence f is true. Consider 3 identical red balls and 2 identical orange balls that are usable as markers. These are denoted by $m_{11}, m_{12}, m_{13}, m_{21}$, and m_{22}. A red-colored cube kept on a flat surface can serve as a marker and be described as $\exists x(Cube(x) \bigwedge Color(x, Red))$. We focus on the logical description of a marker rather than its physical realization in the real world. The logical description $(Sphere(x) \bigwedge Green(x))$ of a marker can be implemented using spheres of different radii, with different shades of green color, but we limit ourselves to the description $(Sphere(x) \bigwedge Green(x))$. $L(m_{ij})$ denotes the logical description of marker m_{ij}. All markers of same type have the same logical description. So $\forall\ i, j, k(L(m_{ij}) = L(m_{ik}))$.

Seven requirements for a correct and an efficient usage of markers have been reported in the rest of the paper. No combination of the logical descriptions of markers should imply any stimulus that does not already have any $L(m_{ij})$ in it. To satisfy this, we require that $\forall s_i, 1 \leq i \leq \mid B \mid (s_i \not\subset (\bigcup_{j=1}^{Z} L(m_{j1})))$, where each s_i is the original stimulus before any marker is placed (**Requirement 1**). This prevents any combination of markers from being perceived as an object without markers. This also prevents a placement of markers on markers.

The logical description of a marker implies some conjunction of predicates in some stimulus/stimuli related to the internal state that the marker replaces. In the example of dish collection, the dark blue cube implies the existence of the table. When a marker m_{ij} is introduced, $L(m_{ij})$ replaces some conjunction of predicates in the stimulus of some behavior. If this conjunction is f_1, then we have $L(m_{ij}) \Rightarrow f_1$. Introduction of m_{ij} replaces the internal state needed to determine that f_1 is true.

α_{ij} denotes the logical conjunction in the original stimuli of behaviors that is replaced by $L(m_{ij})$. We assume that the markers are such that $t(L(m_{ij})) << t(\alpha_{ij})$ (**Requirement 2**). This means that the time needed to recognize markers is much less than the time needed to recognize the internal models they replace. If markers do not satisfy this, there may not be any computational savings obtained with their introduction. No combination of markers should be perceived as some other marker. Similarly, no combination of percepts with markers should be viewed as some other percept with markers. It is computationally expensive to first design markers and then check if these criteria are satisfied. These criteria are easily satisfied if each type of marker has a unique feature. This is satisfied if $\forall\ 1 \leq j \leq Z((L(m_{j1}) - (\bigcup_{p=1,p\neq j}^{Z} L(m_{p1}))) \neq \phi)$ (**Requirement 3**). To avoid an undesirable outcome, we do not want markers to modify a stimulus s_i to s_i' such that s_i' is same as some other stimulus that has not been modified by markers. The logical description of any marker should not coincide with the logical descriptions of existing percepts without markers that may serve as stimuli. Such a coincidence can mislead the robot. The robot then may manipulate markers, ignoring real objects relevant to its behaviors. The robot may then put markers on markers. The robot may then put non-marker objects on markers. This type of behavior is avoided if $L(m_{ij}) \not\subset (\bigcup_{k=1}^{|B|} s_k)$ is satisfied for all $i, 1 \leq i \leq Z$, where $\bigcup_{k=1}^{|B|} s_k$ is the union of the original stimuli that are not modified by markers (**Requirement 4**). This prevents a collection of non-marker objects from being perceived as a marker.

We have the following four laws governing the logical descriptions of markers $(L(m_{ij}), L(m_{pq}))$ and the logical formulae f_1 and f_2 with which the replaced internal states are associated. g is an arbitrary logical sentence that is not affected by the introduction of markers. f_1, f_2 and g are not logical descriptions of markers. These four laws maintain consistency between the logical descriptions of the markers and the internal states they replace.

1. If $((L(m_{ij}) \Rightarrow f_1) \wedge (L(m_{pq}) \Rightarrow f_2))$ then $((L(m_{ij}) \wedge L(m_{pq})) \Rightarrow (f_1 \wedge f_2))$.
2. If $((L(m_{ij}) \Rightarrow f_1) \vee (L(m_{pq}) \Rightarrow f_2))$ then $((L(m_{ij}) \vee L(m_{pq})) \Rightarrow (f_1 \vee f_2))$.
3. If $(L(m_{ij}) \Rightarrow f_1)$ then $((L(m_{ij}) \wedge g) \Rightarrow (f_1 \wedge g))$.
4. If $(L(m_{ij}) \Rightarrow L(m_{pq}))$ then $(\alpha_{ij} \Rightarrow \alpha_{pq})$.

We assume that markers of the same type are used to replace only one logical conjunction which may occur in several stimuli. Without this, conflicting behaviors may occur. Assume that we have behaviors for picking dishes, loading dishes into a dishwasher and picking books. Some of the predicates in the stimuli of some of these behaviors are $Dish(x)$ and $Book(x)$. If the same types of markers are put on dishes and books, books may be loaded into the dishwasher.

When a marker is used to replace internal state, one can either place the marker on every object in the environment that satisfies the relevant subset of predicates in the stimuli of some behaviors, or on fewer objects. We refer to this latter case as *local replacement of internal* *state*. For example if there are multiple tables such that no dish on any of those is to be moved to the sink, one can either keep a dark blue cube on each of them (global replacement of internal state) or only on some of them (local replacement of internal state). The markers used at the AAAI robot competitions and RoboCup competitions can be considered as doing global replacement of internal state. When a marker is introduced to replace the internal state of a behavior, the stimulus of the behavior must be adapted to this change. Consider a behavior β_2 and a marker m_{31} such that $s_2 = (p_1 \wedge p_2 \wedge p_3)$ and $L(m_{31}) \Rightarrow (p_1 \wedge p_2)$. In case of local replacement of internal state, we modify s_2 to $(p_1 \wedge p_2 \wedge p_3) \vee (L(m_{31}) \wedge p_3)$ (thus changing the purely conjunctive nature of s_2). Note that though $(p_1 \wedge p_2)$ continues to exist in the new stimulus in disjunctive normal form, we do have savings in the computation associated with the use of internal state. We do not always have to match a percept with the internal state associated with $(p_1 \wedge p_2)$, in order to determine if the stimulus is true. In case of global replacement of internal state, we modify s_2 to $(L(m_{31}) \wedge p_3)$.

In general, an object satisfying α_{ij} will not necessarily have the marker m_{ij} on it. However the reverse is true - an object with the marker m_{ij} on it will satisfy α_{ij}, assuming that the replacement of internal state is *fair* in the sense that markers are not put on irrelevant objects (**Requirement 5**). We assume fair replacement of internal state in this paper. In case of global replacement of internal states, internal models like models of chairs, tables, shelves and cups can be permanently removed from the robot's memory if (i) these models are not needed to evaluate the truth of other stimuli, (ii) markers placed once are not going to be removed, and (iii) if objects similar to the ones with markers are going to be introduced in the world, they will be introduced with similar markers. To obtain the benefits of markers, a robot should be programmed to check for the truth of the conjunctions in the stimuli involving $L(m_{ij})$ before other conjunctions, especially when the stimulus is disjunctive as in local replacement of internal state. We require that $(\alpha_{ij} - L(m_{ij})) \neq \phi$ (**Requirement 6**). This ensures that a marker is not perceived as something that can be augmented with markers. This avoids a placement of markers on markers.

In general, multiple markers of different types may be used to replace different logical conjunctions in the same stimulus. Next we give the general forms of new stimuli obtained after markers are used. When markers of different types are used to replace different conjunctions in stimulus s_k and local replacement of internal state is used, the stimulus s_k is replaced by $((L(m_{ij}) \wedge L(m_{pq}) \wedge L(m_{rs}) \wedge .... \wedge \text{Ł}(m_{ab})) \wedge (s_k - (\alpha_{ij} \wedge \alpha_{pq} \wedge \alpha_{rs} \wedge .... \wedge \alpha_{ab}))) \vee s_k$. When global replacement of internal state is used and multiple markers of different types are used to replace the internal state, the stimulus s_k is replaced by $((L(m_{ij}) \wedge L(m_{pq}) \wedge L(m_{rs}) \wedge .... \wedge \text{Ł}(m_{ab})) \wedge (s_k - (\alpha_{ij} \wedge \alpha_{pq} \wedge \alpha_{rs} \wedge .... \wedge \alpha_{ab})))$. When markers of the same type are used to replace internal state related to s_k and local replacement of internal state is used, the stimulus s_k is replaced by $(L(m_{ij}) \wedge (s_k - \alpha_{ij})) \vee s_k$. When global replacement of internal state is used and markers of same type are used to replace some internal state, s_k is replaced by $(L(m_{ij}) \wedge (s_k - \alpha_{ij}))$. Note that the previous four cases involving local/global replacement of internal state using one or multiple types of markers for a single stimulus introduce at the most one OR operator in the stimulus. We assume that only one type of marker is used to replace a specific conjunction from stimuli. This reduces the disjunction in stimuli, keeping the average time needed to determine the truth of stimuli low, as we show next. It may be possible to use a yellow ball (marker m_{11}) or a red cube (marker m_{22}) to replace conjunction $(a \wedge b)$ from the stimuli of behaviors. If yellow balls are put on some objects satisfying $(a \wedge b)$ and red cubes are put on some other objects satisfying $(a \wedge b)$, then a conjunctive stimulus s_i containing $(a \wedge b)$ must be changed to $((L(m_{11}) \wedge (s_i - \{a, b\})) \vee (L(m_{22}) \wedge (s_i - \{a, b\})) \vee s_i)$, in case of local replacement of internal state. Note that in general this will introduce n OR operators in a stimulus, if there are n types of markers used to replace the same conjunction and local replacement of internal state is used. This increases the average time needed to check if a stimulus is true. Also, then more internal models need to be stored to detect markers. Internal models of both yellow ball and red cube need to be stored. Using same type of marker to replace a conjunction introduces at the most one OR operator in the logical description of a stimulus. A marker is recognized based on its logical description. We assume that a robot's motor actions do not destroy or remove any marker. This assumption holds at the AAAI and RoboCup competitions.

3. Properties of Markers

A marker set is **redundant** if there exists a non-empty set of distinct types of markers $\{m_{ij}, m_{pq}, m_{ab}, m_{cd}, m_{ef}, ..., m_{gh}, m_{rs}\}$ such that $((\alpha_{ij} \wedge \alpha_{pq} \wedge \alpha_{ab} \wedge \alpha_{cd} \wedge \alpha_{ef} \wedge ... \wedge \alpha_{gh}) = \alpha_{rs})$. Redundancy is related to the amount of internal models needed to recognize markers. If a marker set is redundant, more is the space needed to store internal models. A marker m_{ij} is more **efficient** than marker m_{pq} if $t(m_{ij}) < t(m_{pq})$, that is, the time required to recognize m_{ij} is less than the time required to recognize m_{pq}.

- **Mutually Exclusive Markers:** Let m_{11} and m_{34} be markers such that $\alpha_{11} = (Tall(x) \wedge Chair(x))$ and $\alpha_{34} = (Short(x) \wedge Chair(x))$. Clearly, a chair cannot be both tall and short. The conjunction $(Tall(x) \wedge Short(x))$ is a contradiction. If both m_{11} and m_{34} are placed on the same chair, behaviors involving short and tall chairs will be triggered and this may lead to an undesirable outcome. This leads to the notion of mutex markers (mutually exclusive). Markers $m_{ij}, m_{ab}, m_{cd}, m_{ef}, m_{ac}, m_{ad}, ..., m_{pq}$ are mutex if $(\alpha_{ij} \wedge \alpha_{ab} \wedge \alpha_{cd} \wedge \alpha_{ef} \wedge \alpha_{ac} \wedge \alpha_{ad} ... \wedge \alpha_{pq})$ is a contradiction. Clearly, mutex markers should not be placed on the same percept (**Requirement 7**). The placement of markers is *consistent* if no percept has mutex markers.

4. Semi-Automatic Introduction of Markers

In this section, we report on a semi-automatic approach to place markers. We assume that there is a single robot which is the only mobile object in its world. The designer of behaviors or somebody with some knowledge about the behaviors identifies the longest conjunctions in each stimulus such that (i) internal state is needed to determine that these conjunctions are true, (ii) these conjunctions can be replaced by logical descriptions of markers, and (iii) no behavior of the robot makes any predicate from any of these conjunctions false. If condition (iii) is not satisfied and markers are placed, we will have markers on percepts in undesirable states. This can trigger an undesirable behavior. For example, let us consider the behavior of picking a dish from table only. The stimulus of this behavior is $(Dish(x) \wedge Table(y) \wedge On(x, y))$. A marker m_{ij} can be put on a dish and one can modify the stimulus to $(L(m_{ij}) \wedge Table(y) \wedge On(x, y))$. In this case, $\alpha_{ij} = Dish(x)$ and

$L(m_{ij})$ is $(Cube(z) \wedge On(z,x))$. One may think of getting an additional replacement of internal state by putting the markers only on dishes that are on tables and in that case, $\alpha_{ij} = (Dish(x) \wedge Table(y) \wedge On(x,y))$ and the stimulus becomes just $L(m_{ij})$. There is a problem with this option. The dish can be picked up and moved to other places, with the marker still on it. The behaviors that require the dish to be initially on table will still be triggered since the dish still has the marker. This requires removal of markers which is outside the scope of the Place-Markers algorithm. Note that $Dish(x)$ and $Table(y)$ are invariants. $On(x,y)$ is not an invariant, since x can be moved. Let the list of human-identified conjunctions satisfying the three conditions in this section be denoted by I. For example, consider $B = \{\beta_1, \beta_2, \beta_3, \beta_4\}$ such that $s_1 = (a_1 \wedge a_2 \wedge a_3)$, $s_2 = (a_4 \wedge a_5 \wedge a_6 \wedge a_7)$, $s_3 = (a_8 \wedge a_9 \wedge a_{10})$, and $s_4 = (a_{11} \wedge a_{12})$. Let I be $((a_1 \wedge a_2), (a_2 \wedge a_3), (a_4 \wedge a_5 \wedge a_7), (a_8 \wedge a_{10}), (a_{11} \wedge a_{12}))$. Since the length of I is 5 and a marker is used to replace only one conjunction, multiple copies of 5 markers can be placed in the robot's world. The finite set of these markers is $\{m_{11}, m_{12}, ..., m_{21}, m_{22}, ..., m_{31}, m_{32}, ..., m_{41}, m_{42}, ..., m_{51}, m_{52}, ...\}$. Furthermore, the robot is programmed so that i th member of I is same as $\alpha_{ij}, \forall j$. This means that the robot can replace i th member of I from the stimulus of a behavior by $L(m_{ij})$ after placing marker m_{ij} on an object satisfying the i th member of I. If the robot's world is a house, I might be $((Table(x)), (Shelf(x) \wedge Has-three-compartments(x)), (Computer(x) \wedge Has-big-screen(x)), (Medium-glass(x) \wedge Has-handle(x)))$.

Given below is an algorithm where the robot explores its world for a finite time and places markers on objects that are time-consuming to recognize. θ is a user-specified threshold. S

is the set of markers of various types. $p(\gamma)$ denotes the position of logical conjunction γ in list I. ψ too is a user-specified threshold. In brief, the algorithm places markers on objects that are time-consuming to recognize, and updates the set of remaining markers and updates the relevant stimuli.

```
Place-Markers($\theta, S, I, \psi$)
$S' = S$.
While (time-spent $< \theta$)
{ Make a collision-free move in a random direction.
If ((an object $A$ satisfying some member $\gamma$ of $I$ is found) & ($t(\gamma) > \psi$))
then { Put marker $m_{p(\gamma)j}$ on $A$.
$S' \longleftarrow (S' - m_{p(\gamma)j})$.
$\forall s_i$ that are purely conjunctive, do $s_i \longleftarrow (((s_i - \gamma) \wedge L(m_{p(\gamma)j})) \vee s_i)$ if $\gamma \in s_i$. } }
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The algorithm performs a local replacement of internal state using at the most one type of marker to modify a single stimulus. Note that once some relevant marker is used, the stimuli become disjunctive and will not be updated further. So the modified stimuli will have at the most one OR operator in their logical expressions. To do a global replacement of the internal state, a robot will need a map of the world or a strategy to explore the entire world. A robot can use Place-Markers algorithm with $3 * n$ extra behaviors where n is the number of markers. n of these behaviors are needed to find different types of markers. n behaviors are needed to pick the n different types of markers. n behaviors are needed to drop n different types of markers. The Place-Markers algorithm requires a human to specify θ, ψ

and also I and S. This is a one-time effort for a given world. Since perception is continuous, we expect the computational savings obtained by the placement of markers to be more than the human effort. The algorithm and the one-time human effort continue to be beneficial even if the world is extended by inclusion of objects of existing object types such that this inclusion does not hide the markers already put. The algorithm uses a marker of at the most one type to replace the internal state associated with a single stimulus. The logical expression representing any stimulus is not a contradiction (otherwise there is a problem with the behavior design that needs to be corrected first). There are no percepts in the world that satisfy a contradictory logical description. So the Place-Markers algorithm does not place mutex markers on the same percept. Hence the algorithm generates a consistent placement of markers. Place-Markers algorithm continues to be correct even if the positions of the existing objects (with or without markers) are changed, as long as the markers are not removed.

5. Discussion

In this section, we discuss possible modifications of the Place-Markers algorithm. At the end, we report on guidelines for correctly and efficiently using markers.

5.1 Extensions of the Marker-Placement Algorithm

The algorithm for placing markers from section 4 can be modified in several ways. A robot can keep a record of the parts of the world visited and in fact carry out a global replacement of internal state. We assumed that $t(L(m_{ij})) << t(\alpha_{ij})$, that is, the time needed to recognize markers is much less than the time needed to determine the truth of the logical formula they replaced from a stimulus. If it is not known whether $t(L(m_{ij})) << t(\alpha_{ij})$ holds, the robot can be programmed to find out $t(L(m_{ij}))$ and autonomously compare it with $t(\alpha_{ij})$, to determine if the placement of m_{ij} will yield any savings. A human can supply the locations where markers may be put, to the Place-Markers algorithm. This will result in a placement of markers that does not interfere with the successful operation of the robot. A robot can be programmed to have behaviors of removing markers and placing them in a bin, whenever the states replaced by markers are no longer valid. Consider a marker that is put on a dish on a table to identify the dish in the state of being on the table. If the dish is moved, the marker should be removed as well. A human can provide the knowledge of variant and invariant predicates to the robot, so that it can remove the markers used to replace the internal state associated with the variant predicates. Variant predicates are also known as fluents. A robot can also keep a record of the behaviors executed over time and remove markers from the percepts that did not make the stimulus of any recently-executed behavior true. The stimuli need to be maintained carefully when a robot has the ability to remove markers. In such a case, the robot needs to store original stimuli before markers were introduced and use them when necessary. For example, consider the stimulus $(L(m_{ij}) \wedge b \wedge c)$ obtained from stimulus $(a \wedge d \wedge b \wedge c)$ when a global replacement of internal state is carried out. If markers $m_{ij}, m_{iq}, m_{is}, ...$ are removed from all percepts satisfying $(a \wedge d)$, then the stimulus $(L(m_{ij}) \wedge b \wedge c)$ should be replaced by $(a \wedge d \wedge b \wedge c)$. If they are removed from only some of the percepts satisfying $(a \wedge d)$, the stimulus should be changed to $(L(m_{ij}) \wedge b \wedge c) \vee (a \wedge d \wedge b \wedge c)$. When markers may be removed, internal models cannot be permanently removed from the robot's memory. These internal models will be needed to evaluate the truth of stimuli after markers have been removed. These models need not be used though as long as markers are around.

5.2 Guidelines for Introducing Markers

In this section, we report on guidelines for correctly and efficiently using markers.

1. The placement of a marker m_{ij} on object A should not hide any feature f of A relevant to a successful operation of the robot.

2. Markers of more than one type should not be used to replace the same conjunction from stimuli.

3. Markers should satisfy the seven requirements from sections 2 and 3.

4. If there are no behaviors for removing markers, a marker m_{ij} should be used only if α_{ij} is an invariant.

Multiple markers of the same type can be kept on the same percept in order to enable faster recognition of the percept. A robot may recognize markers only if its sensors are in a specific geometric configuration. Placing multiple markers of same type on a percept may improve the chances of them being perceived by the robot from an arbitrary configuration.

6. A Case Study

In this section, we illustrate the modification of stimuli when markers are introduced and the mutual exclusivity and efficiency of markers. We discuss the placement of markers in an environment consisting of small and big tables and small and big shelves. The environment and markers are shown in Fig. 1. DRB, DOB, DBC and DRP in Fig. 1 are the markers. A big shelf is a shelf with five compartments. A small shelf is a shelf with three compartments. A big table has a larger surface area than a small table. The robot operating in this world has behaviors for wandering, collision avoidance, cleaning big tables, cleaning small tables, cleaning big shelves and for cleaning small shelves. Recognizing a big shelf without markers requires the robot to store a geometric model of the shelf and compare it with the percepts. This is time-consuming. So markers in the form of dark blue cubes are put on the big shelves. Recognizing a small shelf based on its internal model is similarly time-consuming. So a marker in the form of dark red pyramid is kept on the small shelf. Recognizing a table based on internal state involves storing a geometric model involving a flat surface and four legs and its comparison with the percept. Since this is time-consuming, markers are kept on big and small tables. Stimuli for the various cleaning behaviors are as follows:

$clean - big - table$ - $s_1 = (Table(x) \wedge Big(x) \wedge Dirty(x))$

$clean - small - table$ - $s_2 = (Table(x) \wedge Small(x) \wedge Dirty(x))$

$clean - big - shelf$ - $s_3 = (Shelf(x) \wedge Big(x) \wedge Dirty(x))$

$clean - small - shelf$ - $s_4 = (Shelf(x) \wedge Small(x) \wedge Dirty(x))$

The consequence of each of these behaviors is $(clean(x) \wedge \neg Dirty(x))$. The new stimuli after the introduction of markers are

$clean - big - table$ - $s_1 = (Ball(y) \wedge Color(y, Dark - Red) \wedge On(y, x) \wedge Dirty(x))$

$clean - small - table$ - $s_2 = (Ball(y) \wedge Color(y, Dark - Orange) \wedge On(y, x) \wedge Dirty(x))$

$clean - big - shelf$ - $s_3 = (Cube(y) \wedge Color(y, Dark - Blue) \wedge On(y, x) \wedge Dirty(x))$

$clean - small - shelf$ - $s_4 = (Pyramid(y) \wedge Color(y, Dark - Red) \wedge On(y, x) \wedge Dirty(x))$

The logical descriptions of markers logically imply predicates, the determination of whose truth needs internal state. These implication relations are as follows:

$(Ball(y) \wedge Color(y, Dark - Red) \wedge On(y, x)) \Rightarrow (Table(x) \wedge Big(x))$

$(Ball(y) \wedge Color(y, Dark - Orange) \wedge On(y, x)) \Rightarrow (Table(x) \wedge Small(x))$

$(Cube(y) \wedge Color(y, Dark - Blue) \wedge On(y, x)) \Rightarrow (Shelf(x) \wedge Big(x))$

$(Pyramid(y) \wedge Color(y, Dark - Red) \wedge On(y, x)) \Rightarrow (Shelf(x) \wedge Small(x))$

The conjunctive descriptions on the left hand sides of the implications in the previous four expressions are logical descriptions $L(m_{11}), L(m_{12}), L(m_{21})$, $L(m_{31}), L(m_{32})$, and $L(m_{41})$. The conjunctions on the right hand sides of the implications in the previous four expressions are $\alpha_{11}, \alpha_{12}, \alpha_{21}$, α_{31}, α_{32}, and α_{41}. Some of the contradictions in this domain are $(Shelf(x) \wedge Table(x))$, $(Small(x) \wedge Big(x))$. The placement of markers in Fig. 1 is consistent since it avoids these contradictions.

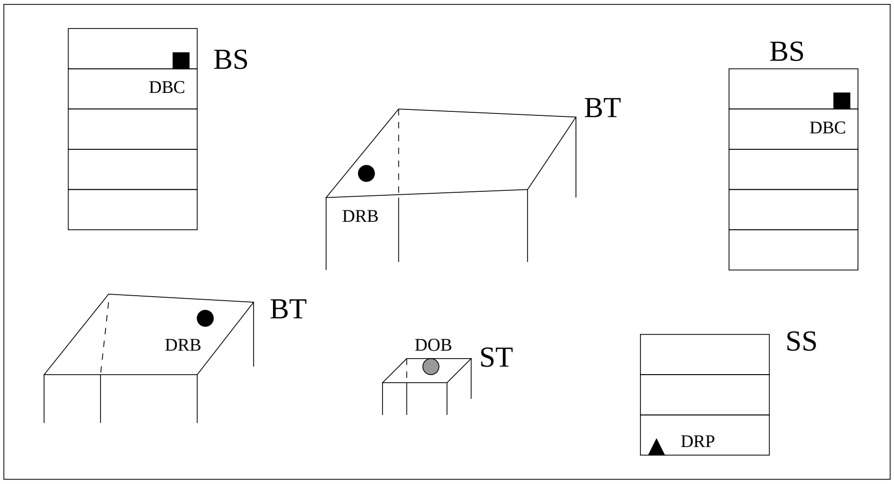

Figure 1: Six objects and six markers on them. BS: Big Shelf, BT: Big Table, ST: Small Table, SS: Small Shelf, DRB: Dark Red Ball, DOB: Dark Orange Ball, DBC: Dark Blue Cube, DRP: Dark Red Pyramid.

7. Conclusion

The previous research on autonomous robots has focused on intelligent modifications to the internal computational structure of a robot, ignoring the modifications to external environments. We bridged this gap by formalizing the replacement of internal state, through an introduction of markers. We provided semantics for markers. We introduced metrics for evaluating markers, like efficiency, redundancy and mutual exclusivity. We showed how to automatically modify behaviors' stimuli when markers are introduced. We reported on an algorithm for an autonomous robotic placement of markers, along with its possible modifications. We also reported on guidelines for effectively and correctly placing markers in a robot's world.

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Amol Dattatraya Mali was born in Pune, India. He received B.E from VJTI, Bombay in 1991, M.Tech from IIT Kanpur in 1994 and Ph.D in Computer Science from ASU in 1999. He was lucky to get great mentors like Subbarao Kambhampati, Robin Murphy, and Amitabha Mukerjee during his graduate study in artificial intelligence. He joined the Electrical Engineering and Computer Science department of University of Wisconsin, Milwaukee as an Assistant Professor in August 1999. He has published 8 journal papers and 26 conference papers. His areas of research are automated planning and autonomous agents.