Spatial Reasoning and Planning in Sign-Based World Model

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Abstract. The paper discusses the interaction between methods of modeling reasoning and behavior planning in a sign-based world model for the task of synthesizing a hierarchical plan of relocation. Such interaction is represented by the formalism of intelligent rule-based dynamic systems in the form of alternate use of transition functions (planning) and closure functions (reasoning). Particular attention is paid to the ways of information representation of the object spatial relationships on the local map and the methods of organizing pseudo-physical reasoning in a sign-based world model. The paper presents a number of model experiments on the relocation of a cognitive agent in different environments and replenishment of the state description by means of the variants of logical inference.

Keywords: Sign · Sign-based world model · Relocation planning
Reasoning modeling · Pseudo-physical logic

1 Introduction

One of the long-standing problems in artificial intelligence is the problem of the formation or setting of the goal of actions by an intelligent agent, for the achievement of which it synthesizes the plan of its behavior. The study of the goal-setting process [1,2] showed that the formation of a new goal in many important cases is connected to the reasoning in the sign-based world model of the actor. In other words, reasoning is an integral part of the process of generating a new goal and hence the planning process. A number of artificial intelligence studies related to goal-driven autonomy [3] also indicate that an important step in the planning process is some formal conclusion aimed at eliminating cognitive dissonance caused by new conditions that require a change or the formation of a new goal.

This work is devoted to the study of one type of interaction. Consideration of such interaction is conducted in the context of intelligent rule-based dynamic systems [4–6]. We consider the problem of spatial planning and reasoning using

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elements of pseudo-physical logic [7]. There is a well-known approach to representing information about an environment as a semantic map [8–10] that mixes different structures such as a metric map, a grid map, a topological graph, etc. The papers [11,12] describe a hierarchical approach to planning the behavior of an intelligent agent, in which abstract geometric reasoning is used to describe the current situation. Also, the algorithm uses a probabilistic representation of the location of objects. The hierarchical refinement of the surrounding space used in the article is justified from the viewpoint of reducing the time spent by the agent for recognizing the surrounding space, but preserving all refined knowledge and generating possible actions leads to unnecessary load on the processor of the agent, which negatively affects its speed. The approach in [13] describes the activity of an agent that uses logic derived from studies of rat brain activity in performing tasks related to spatial representation. The hierarchy of the map views reduces the noise caused by the remoteness from the agent of some parts of the map, to which linear search trajectories were built (paths to the target from the current location). Keeping all possible trajectories to any part of the environment requires additional resources from the agent, significantly reducing the speed of decision making by the agent. If there is a dynamic space in which other agents work and the location of the objects can change, the approach will require too much resources to calculate all possible outcomes of activities. These problems were partially addressed in [14,15], which led to the creation of the RatSLAM system, which allowed the agent to travel long distances in real terrain.

In our case, the representation of spatial knowledge, planning processes and reasoning is formalized in terms of a sign-based world model [1]. As a demonstration of the proposed approach a number of model experiments on the relocation of a cognitive agent in various environments and state replenishment with one of the variants of logical inference are presented.

2 Sign Approach to Spatial Knowledge Representation

The concept of a sign-based world model for describing the knowledge of a cognitive agent about the environment and himself was introduced in [1,2]. The main component of the sign world model is the sign represented at the structural description level (according to [16]) as a quadruple $s = \langle n, p, m, a \rangle$, where $n \in N$, $p \subset P$, $m \subset M$, $a \subset A$. N is a set of names, i.e. a set of words of finite length over some alphabet, P is a set of closed atomic formulas of the first-order predicate calculus language, which is called the set of images. M is a set of significances. A is a set of personal meanings.

In the case of the so-called everyday sign-based world model, which we will consider below, the image component of the sign participates in the process of recognition and categorization. Significances represent fixed script knowledge of the intellectual agent about the subject area and the environment, and personal meanings characterize his preferences and current activity context. The name component binds the remaining components of the sign into a single unit (naming).

At the structural level of the sign-based world model description each component of the sign is a set of causal matrices that are represent a structured set of references to other signs or elementary components (in the case of an image, these are primary signs or data from sensors, in the case of personal meaning - operational components of actions). The causal matrix allows the encoding of information to represent both declarative and procedural knowledge. A set of sign components forms four types of causal networks, special types of semantic networks. Modeling of planning and reasoning functions is carried out by introducing the notion of activity (the set of active signs or causal matrices) and the rules of activity propagation on various types of networks [17]. In progress of a cognitive function, new causal matrices are formed, which can then be stored in the components of the new sign, similar to the experience preservation in systems based on precedents.

3 Dynamical Intelligent Systems

Let us introduce the basic concepts from the theory of intelligent rule-based dynamic systems following [5]. First of all, we will distinguish the main components of the system: working memory, in which a set of facts are stored (i.e. closed formulas of the first-order predicate calculus language), a set of rules and strategies for selecting rules.

The rule is the ordered triple of sets $r = \langle C, A, D\rangle$, where C is a condition of the rules, A is a set of facts added by the rule, D is a set of facts deleted by the rule. A special variable $t \in T$ is distinguished, where T is a discrete ordered set, is related to the discrete time. Thus, the concrete value of the variable t corresponds to a specific moment in time. The set of rules Π is divided into two subsets Π_{CL} and Π_{TR}. The set Π_{CL} consists of rules that do not correspond to any actions, their application only replenishes set of facts of the state (working memory). Such rules are called as the rules of communication, and the set Π_{CL} is called the set of rules for the closure of states. The set Π_{TR} includes rules defining actions, such rules are called transition rules, and the set itself is the set of transition rules. A distinctive feature of the transition rules is that the value of t changes at least by one for the conditions of the rule and the set of added and deleted rules:

$$\Pi_{CL} = \langle C\left(t\right), A\left(t\right), D\left(t\right)\rangle,$$
$$\Pi_{TR} = \langle C\left(t\right), A\left(t+1\right), D\left(t+1\right)\rangle.$$

Rules are applied to working memory, which, in turn, changes its state. The rule selection strategy determines which of the possible rules will be applied and terminates the application when the state of the working memory satisfies the target condition.

Let CL and TR be the strategies for applying the rules Π_{CL} and Π_{TR}, X be the set of facts, respectively. Then the strategy CL realizes a mapping $2^X \rightarrow 2^X$, and the strategy TR is a mapping $2^X \times T \rightarrow 2^X$. We introduce the functions

$$\Phi(\chi(t)) = (CL, \chi(t)) : 2^X \to 2^X,$$
$$\Psi(\chi(t), t) = (TR, \chi(t), t) : 2^X \times T \to 2^X.$$

Function Φ is called the closure function, it replenishes the description of the current state of the system. Function Ψ is called a transition function, it takes the system from one state to another.

Thus, a quadruple $D = \langle X, T, \Phi, \Psi \rangle$ is called an intelligent rules-based dynamic system.

Let us clarify the definitions introduced for the case of modeling reasoning and planning of relocation in the sign-based world model.

In the sign-based world model working memory and set of facts of the state will correspond to a set of active signs from which the description of the current situation is constructed (the causal matrix on the network of personal meanings), and the rules of the dynamic system correspond to rules for activity propagation in causal networks that change the set of active causal matrices and description of the current situation. Then the initial state of the working memory will correspond to the initial situation, and the state of the working memory that satisfies the target condition is the target situation.

The process of modeling is divided naturally into two stages: reasoning and planning actions, in our case, relocation. Moreover, while reasoning, obviously, only a change in the description of the current situation occurs (changing the world model of the agent) without modeling any actions in the environment. This process corresponds to the application of the closure function Φ to the working memory. In the process of relocation planning, the agent considers possible actions in the environment and the consequences of such actions, therefore, such a process can be associated with a function Ψ. Then the cognitive rule-based dynamic system defined in the sign-based world model is the quadruple $D_{SWM} = \langle X_{SWM}, T, \Phi_{SWM}, \Psi_{SWM} \rangle$, where X_{SWM} stays for the semiotic network and procedural matrices; T is discrete time; Φ_{SWM} are rules for activity propagation on causal networks in the implementation of the reasoning function; Ψ_{SWM} are rules for the activity propagation on causal networks in the implementation of the planning function.

4 Integration of Reasoning and Planning

The transition function Ψ is implemented due to the rules for activity propagation, designed as a MAP planning algorithm [17]. The MAP algorithm allows the cognitive agent with the sign-based world model to synthesize the optimal path to the required location on the map. The agent's sign-based world model for the relocation task includes elementary signs of objects, signs of actions, signs of spatial and quantitative relations modeling the relations of pseudo-physical logic [7], as well as signs of cells and regions (see Fig. 1) [18]. The process of map recognition by the agent begins with the stage of determining the regions. The map is divided into 9 identical segments that denote the "Region" sign. The regions do not have a fixed size and their area is calculated depending on the size of the map. The regions can contain objects, agents, obstacles, and cells. The cells are map segments obtained by dividing the larger segments (in the first step of recognition the segment is the region) by 9 equal parts until the central cell contains only the agent. As soon as such a cell is formed (its size cannot be less than the diameter of the agent), it is represented by the "Cell" sign. Further, around it, an additional 8 cells are built that describe the current situation. After that, the process of plan synthesis, presented in Algorithm 1, begins. It consists of two stages: the stage of replenishment of the agent's world model (step 1) and the stage of plan synthesis (steps 2–20).

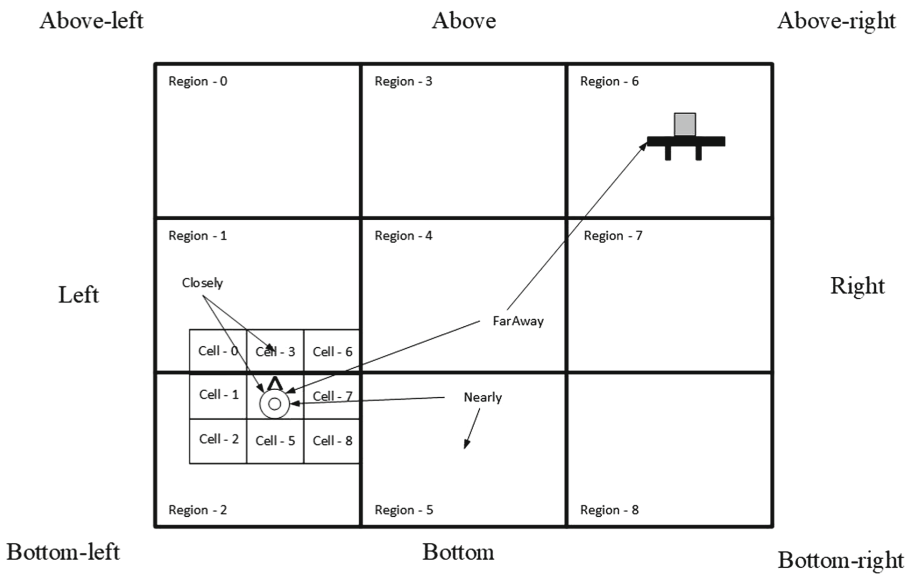

Fig. 1. Illustration of spatial relationships, cells and regions of the sign world model

The replenishment phase of the agent's world model begins with the creation of signs and causal matrices for objects (including cells and regions), their types, predicates and actions obtained from recognition of the map and the planning task, as well as the creation of the sign "I" [18]. Next, the agent creates causal matrices of the initial and final situations and locations on the map.

At the stage of plan synthesis, the agent recursively creates all possible plans to achieve the final situation, which describes the agent's target location on the map. To do this, in Step 7, the agent looks at all the signs that are included in the description of the current situation, and in Steps 8–9, using the activity propagation process over the network of significances, procedural action matrices are activated. Using the processes described in steps 10–12, action matrices are updated, replacing references to role signs and object types with references to specific task objects. Next, there is a step of choice $A_{checked}$ - actions that are heuristically evaluated, as the most appropriate in the situation $z_{sit-cur}$ to achieve the situation $z_{sit-goal}$. After that, from the effects of each action $A \in A_{checked}$ and the references to the signs that enter the current situation $z_{sit-cur+1}, z_{map-cur+1}$ is constructed, which describes the agent's state and the map after applying the action A. At the step 16, the action A and $z_{sit-cur}$ under consideration is added to the plan and, at the step 17, the entry $z_{sit-goal}$ in $z_{sit-cur+1}$, $z_{map-goal}$ in $z_{map-cur+1}$ is checked. If the matrices of the current state include the matrices of the target state, then the algorithm saves the found plan, as one of the possible ones, if not, then the plan search function is recursively repeated (step 20).

1 $T_{agent} := GROUND(map, struct)$
2 $Plan := MAP\_SEARCH(T_{agent})$
3 **Function** MAP_SEARCH($z_{sit-cur}$,$z_{sit-goal}$,$z_{map-cur}$,$z_{map-goal}$,$plan$,i):
4   **if** $i > i_{\max}$ **then**
5   **return** $\emptyset$
6   **end**
7   $z_{sit-cur}, z_{map-cur} = Z^a_{sit-start}, Z^a_{map-start}$
8   $z_{sit-goal}, z_{map-goal} = Z^a_{sit-goal}, Z^a_{map-goal}$
9   $Act_{chains} = getsitsigns\,(z_{sit-cur})$
10   **for** $chain\ in\ Act_{chains}$ **do**
11     $A_{signif}| = abstract\_actions\,(chain)$
12   **end**
13   **for** $z_{signif}\ in\ A_{signif}$ **do**
14     $Ch| = generate\_actions\,(z_{signif})$
15     $A_{apl} = activity(Ch, z_{sit-cur})$
16   **end**
17   $A_{checked} = metacheck(A_{apl}, z_{sit-cur}, z_{sit-goal}, z_{map-cur}, z_{map-goal})$
18   **for** $A\ in\ A_{checked}$ **do**
19     $z_{sit-cur+1}, z_{map-cur+1} = Sit\,(z_{sit-cur}, z_{map-cur}, A)$
20     $plan.append(A, z_{sit-cur})$
21   **if** $z_{sit-goal} \in z_{sit-cur+1}\ and\ z_{map-goal} \in z_{map-cur+1}$ **then**
22       $F_{plans}.append\,(plan)$
23   **end**
24   **else**
25       $Plans := MAP\_SEARCH$
         $(z_{sit-cur+1}, z_{sit-goal}, z_{map-cur+1}, z_{map-goal}, plan, i+1)$
26   **end**
27   **end**

Algorithm 1. Process of plan synthesis by cognitive agent

Thus, the agent forms an action plan using the rules for activity propagation Π_{TR}, changing the current state of the working memory (which consists in the formation and change of causal matrices $z_{sit-cur}$ and $z_{map-cur}$). When the state of working memory is reached, many facts of which include a set of facts that form the final state, the algorithm terminates.

Next, consider the process of reasoning in a sign-world model using elements of pseudo-physical logic.

To determine the location of an object relative to an agent, we define a set I_A^O such that the focus cell k_i^A, $i = 0 \ldots 8$ of the agent's attention belongs to the set I_A^O, if and only if it coincides with any focus cell k_j^O, j $= 0 \ldots 8$ of the object, i.e. focuses of the attention of the agent and the object are intersected in this cell: $I_A^O = \{k_i^A | k_i^A = k_j^O, i, j = 0 \ldots 8\}$ or $I_A^O = \{k_i^A | k_i^A \in F^A \cap F^O, i = 0 \ldots 8\}$,

where F^A, F^O are the focuses of the attention of the agent and the object, respectively. We apply exclusion *Exclude* and absorption *Absorb* operations to the set obtained. The operation *Exclude* checks whether the set I_A^O contains conflicting signs of cells, and if there are such cells, it excludes them. Also, this operation excludes the sign of the cell in which the agent is located, because it does not affect the location definition. The operation *Absorb* excludes a sign with a narrower significance if there is a sign with a wider significance. A set $I_O^A = \{k_j^O | k_j^O \in F^A \cap F^O, j = 0 \ldots 8\}$ is used to determine the location of the agent relative to the object.

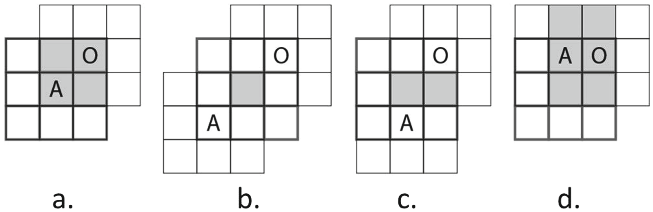

Fig. 2. Examples of the locations of the agent (A) and the object (O)

In Fig. 2 focuses of attention for the agent and the object intersect in four cells, then

$$\begin{aligned}
&I_A^O = \{\text{“Agent”}, \text{“Above”}, \text{“Right”}, \text{“Above-right”}\}\,, \\
&\mathit{Exclude}\left(I_A^O\right) = \{\text{“Above”}, \text{“Right”}, \text{“Above-right”}\}\,, \\
&\mathit{Absorb}\left(\mathit{Exclude}\left(I_A^O\right)\right) = \{\text{“Above-right”}\}\,.
\end{aligned}$$

This implies that the object O is on the right from above with respect to the agent A.

For the case presented in Fig. 2d, we determine the location of the agent A relative to the object O.

$$\begin{aligned}
&I_O^A = \{\text{“Object”}, \text{“Above”}, \text{“Left”}, \text{“Above-Left”}, \text{“Below”}, \text{“Below-Left”}\}\,, \\
&\mathit{Exclude}\left(I_O^A\right) = \{\text{“Left”}\}\,, \\
&\mathit{Absorb}\left(\mathit{Exclude}\left(I_O^A\right)\right) = \{\text{“Let”}\}\,.
\end{aligned}$$

Therefore, the agent A is to the left of the object O.

To determine the distance between the agent A and the object O, we will use the following rules:

1. If {"Agent", "Object"} $\in I_A^O \cup I_O^A$ then A "Closely" O;
2. If {"Agent", "Object"} $\notin I_A^O \cup I_O^A$ and $I_A^O \cup I_O^A \neq \{\emptyset\}$ then A "Close" O;
3. If $I_A^O = I_O^A = \{\emptyset\}$ or, equally, $I_A^O \cup I_O^A = \{\emptyset\}$ then A "Far" O.

The approach presented above implements the closure function Φ, which is described by the mechanism of activity propagation as follows. From the sign of the agent's focus of attention $k_i^A, i = 0 \ldots 8$, the activity, downward, spreads up to the actualization of the sign of the map cell. After that, the activity from the sign of the map cell spreads ascending and if the sign of the object's focus cell $k_j^O, j = 0 \ldots 8$ is updated, the sign of the cell $k_i^A, i = 0 \ldots 8$ is added to the set I_A^O. Procedures *Exclude*, *Absorb* and rules for determining the distance are implemented by the corresponding procedural matrices.

5 A Model Example

As part of the application demonstration of a sign world model to the problem of spatial planning, problems associated with moving an agent in a confined enclosed space are considered. Such a restriction allows us to reveal the advantages of a symbolic representation of spatial logic for the process of planning a route with obstacles and objects in the immediate vicinity of the agent. Here we present an example of scheduling an agent's move to an empty map in experiment 1, an example in which an agent plans to move away from an obstacle and, through logical inference, changes his view of the location of the obstacle in experiment 2 and an example in which the agent plans to bypass the obstacle in experiment 3 (see Fig. 3).

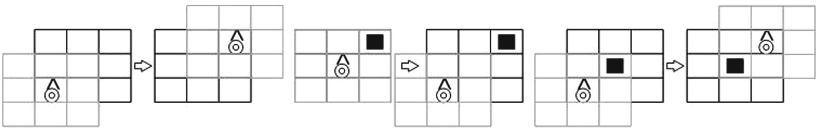

Fig. 3. Experiments 1, 2 and 3

Experiment 1 describes the process of constructing a plan with a length of 4 actions, the first iteration activated the matrix of the "Rotate" sign, which contained a reference to the "Closely" sign relative to the upper right cell and a reference to the sign mediating the direction to this cell. Next, the sign matrix "Move" was activated. At the next iteration, the matrices of signs "Move", "Right-from-top" and "Cell-6", which were referenced in the condition of "Location" matrix, are reactivated. In the final iteration, the matrix of the "Turn" sign was activated, which contained references to signs "Agent Direction" and "Top".

Experiment 2 describes the process of constructing a plan with a length of 3 actions, which includes 2 rotation actions and an action to move to the lower left region. The entire upper right area was occupied by an obstacle from which the agent retreated. At the first iteration of the planning process, the matrix of the "Rotate" sign, describing the change in the direction of the agent, as well as the matrix of the "Location" sign, which included a reference to the "Closely" sign with respect to the obstacle cell, was activated. Then, at the second iteration, the sign matrix "Move" was activated, and the matrix of the "Closely" sign with respect to the mentioned area ceased to be active. With the help of the reasoning process, the matrix of the sign "Close" (related to the area containing the obstacle) was activated. In the described task, matrices activated by the process of reasoning allow the agent not to repeat the process of finding objects that were included in the description of the previous situations of the plan.

In experiment 3, four possible plans were built to achieve the required location of the agent, of which a plan consisting of 6 actions was selected. At the first iteration of the planning, the sign matrix "Rotate" relative to the right upper region was not activated, because, through the heuristics used by the algorithm, the agent is not available actions that direct him to obstacles with which he can not interact. The matrix of the "Rotate" sign was activated, in the effects of which there was a reference to the "Agent Direction" sign, which mediates the direction to the adjacent to the target area. Further, the action plan according to the described heuristic was iteratively constructed.

6 Conclusion

In this paper we have presented an original approach to interacting mechanisms for the synthesis of the behavioral plan by the cognitive agent and reasoning procedures in its sign-based world model. A scheme of such interaction is proposed in the context of intelligent rule-based dynamic systems. The work of this approach in the problem of smart relocation in space is demonstrated.

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