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Hierarchical Psychologically Inspired Planning for Human-Robot Interaction Tasks

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Abstract. This paper presents a new algorithm for hierarchical case-based behavior planning in a coalition of agents – HierMAP. The considered algorithm, in contrast to the well-known planners HEART, PANDA, and others, is intended primarily for use in multi-agent tasks. For this, the possibility of dynamically distributing agent roles with different functionalities was realized. The use of a psychologically plausible approach to the representation of the knowledge by agents using a semiotic network allows applying HierMAP in groups in which people participate as one of the actors. Thus, the algorithm allows us to represent solutions of collaborative problems, forming human-interpretable results at each planning step. Another advantage of the proposed method is the ability to save and reuse experience of planning – expansion in the field of case-based planning. Such extension makes it possible to consider information about the success/ failure of interaction with other members of the coalition. Presenting precedents as a special part of the agent's memory (semantic network on meanings) allows to significantly reduce the planning time for a similar class of tasks. The paper deals with smart relocation tasks in the environment. A comparison is made with the main hierarchical planners widely used at present.

Keywords: Cognitive agent · Sign · Sign-based world model · Human-like knowledge representation · Behavior planning · Spatial planning · Pseudo-physical logic · Task planning

1 Introduction

In connection with the development of robotics and automation of the management of complex technical means, the activity of research in the direction of artificial intelligence increases. The actual problem in this area is the complexity of the transition from a symbolic description of the environment to objects which perceptual images are directly observed by the agent. Existing symbolic planning algorithms do not allow the agent to synthesize an action plan based on sensor data from the real environment state. Currently, the most common architecture of robotic agents is the hybrid architecture [1, 2], which responds to the dynamics [3] of the environment and updates the previously synthesized action plan. The hybrid architecture implies the presence of several levels of abstract representations of agent actions in the plan, for example, the HFSM

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structure (parallel hierarchical finite state machine) used in WillowGarage allows the implementation of robot's actions such as delivering food from a refrigerator, playing chess, moving over rough terrain. HFSM considers both a general view of task actions and specific implementations of agent actions. The hierarchy of abstractions of action representation helps reduce time and resource costs for building a plan [4], lowers the level of dissemination of personal information of an agent [5], provides an opportunity to parallelize actions [6], allows you to find and process possible risks of the plan [7], and also allows partially re-planning activities in the environment dynamics [8].

In modern architectures, the hierarchy of abstractions of actions is represented using plans of various levels of detail. Abstract plans generated using classical planning approaches can be refined in the implementation process, and experience describing detailed actions can be reused in subsequent tasks. In this paper, we propose to use the representation of the agent knowledge in the form of a semiotic network, a part of which can be saved at the end of the activity and used in solving subsequent problems. The developed mechanism for limiting the used set of knowledge allows you to deal with a decrease in the rate of search for a plan in the current situation due to the dependence of the dimension of variations of substitutions when planning actions only on the description of the problem being solved. After the completion of the planning process, all the actions found are saved as a subnet of the global knowledge network of the agent, and access to this subnet can be accomplished by moving from the element designating the task to be solved. (This process is described in more detail in Sect. 2). Strictly structuring the sequence of sub-actions is used in modern HTNPlan-P [9], PANDA [10] planners, based on the HTN planning approach, improvements of which provide the ability to partially re-plan [11] in a dynamic environment and limit time execution processes as elementary, and complex actions [12] of the agent. But, unlike the above planners, the approach in question does not contain predefined descriptions of abstract actions (methods, if we speak in terms of HTN), but generates these sequences dynamically based on the task and the available planning precedents.

The behavior planning approach described in this paper allows an agent to use a complex, previously detailed action to select coalition members with whom there have already been successful interaction cases [13]. The HierMAP algorithm uses information both about the capabilities of the planning agent itself and about the capabilities of other team agents. Based on the knowledge of the capabilities of another agent and the experience of previous interactions with him, the decision on the activity's implementation is made. Since the described algorithm performs the planning of the cognitive agent's activity, an appropriate communication protocol is used, transmitting messages between actors in a manner understandable to humans. After the planning process is completed, an auction of plans is carried out in which agents select the final goal plan. This process is described in more detail in Sect. 3.

Modern robotic agents are designed to perform actions in a real environment and require an internal representation of spatial and quantitative relations with respect to each other and the objects with which they interact. Human's spatial relations are directly related to the significances of the objects themselves [14] and with their entry into the focus of attention [15], in which elementary actions are carried out. Forming the focus of a person's attention is based on the concepts of "Left", "Right", "Here", "There", "Close", "Far" and others, which contribute to the awareness of the fact that

"I am here" and the rest of the world is "there". The described algorithm, in contrast to traditional approaches [16, 17], is based on a psychologically-similar way of representing knowledge and uses spatial pseudo-physical logic [18, 19], typical to planners [20, 21] which are commonly used by cognitive agents. A characteristic feature of agents whose actions are synthesized on the basis of psychologically or biologically [22–24] of such ways of representing knowledge in the planning process is the presence of intelligent terrain marking. The agent needs to assess its location and purposefully act by implementing a synthesized plan. The main problem of modern cognitive agents is the accumulation too much knowledge about the environment, which makes it possible to draw a conclusion that a person can understand a real state of an agent [25], but leads to a significant slowdown in his activity. To eliminate this problem, various types of spatial semantic hierarchy [19, 26] are used, allowing robotic agents to act on large maps [27] in a dynamically changing environment. The planning approach presented in this paper allows an agent to have different levels of focus abstraction of attention (situations) and to carry out activities based on the local location of subjects and objects of activity. The possibility of preserving the experience of intersecting a plot of terrain in which a clarification of the situation was required allows one to reuse an abstract action of moving in a similar situation without slowing down the planning process. This process is described in more detail in Sect. 4.

Further article is organized as follows. Section 2 describes the basic principles of the used method of knowledge representation and describes the logic of the HierMAP algorithm. Section 3 presents a description of the multi-agent component of the approach, discloses the principles of agent reflection, role distribution. Section 4 describes the pseudo-physical logic used in the intellectual movement of agents. In Sect. 5, the results of experiments and their discussion are given.

2 Cognitive Agent Subject Activity

The HierMAP algorithm uses a semiotic representation of the agent knowledge [28, 29] the base element is the sign [30–32]. Using the sign structure as a way of presenting knowledge about the elements of the environment was chosen on the basis of research by neurophysiologists and psychologists [33, 34] regarding the representation of knowledge by human. In addition, the possibility of combining different ways of representing knowledge about the same object to move from the classical for artificial intelligence symbolic way of representing knowledge to a hybrid one that meets the principles of robotics of the present time was considered.

2.1 Psychologically Inspired Knowledge Representation

The sign is described by a tuple, which includes 4 main components $s = \langle n, p, m, a \rangle$, where n is the name component, which is used to define the sign, p is the image component, m is the significance component, and a is the personal meaning component. Each of the components of the sign is responsible for its type of presentation of information about the described entity. Component p is a description of the characteristic features of an entity (in HierMAP, this is a description of the coordinates of a terrain segment, or a sequence of sub-actions of an abstract action). Component m - is responsible for the available generalized scenarios for the use of an entity by a group of agents, and component a - determines the role of the represented entity in the action of the planning entity. Personal meanings of the sign are synthesized in the process of the agent with the described entity. A sign can be either a static object or an action.

The components of the sign are represented by a special structure – the causal matrix [35], which allows to connect the components of signs and form semantic networks, the relations on each of which are different. The causal matrix has a structure divided into two parts, the left side is responsible for the conditions of the matrix, and the right side for effects. In the simplest case, the causal matrix can be described using a tuple of length t of events ei. Each of the events on the images network describes the recognized element at the moment of time t1, on the networks of significances and personal meanings – a link to another sign, feature or function of the agent. The described structure of the matrix contributes to the division of matrices into two types: objective and procedural. Procedural matrices describe various actions and processes, therefore, unlike object matrices, they have a non-empty set of effects events.

An example of relations on a images network is the "part-whole" relationship; in the algorithm described, this relationship is used when checking the intersection of the agent's focus and the global part of the map, or the description of the connection between actions of a lower level of abstraction and the action of a larger one due to the connection "action-sub action". On the significances network, characteristic connections are "class-subclass" or "scenario-role" relationships. An example of the implementation of relations of this type can be considered in the task of the well-known domain "Blocks world", in which the block class has subclasses "huge block", "red block", and the role of blocks "block?x" and "block?y" are included in action scenarios "stack". On the network of personal meanings there are "situation-participant of the situation" links, allowing to limit the description of a specific situation to agents who are directly involved in it.

The sign world model is the five elements tuple $\left\langle W_p(s), W_m(s), W_a(s), R_n, \Theta \right\rangle$, where W_m, W_a, W_p – are semantic and causal significances, personal meanings and images networks, respectively, $R = \langle R^m, R^a, R^p \rangle$ are relations on components sign, and Θ - operations on a set of signs. Relationships on the components of a sign allow you to implement the processes of propagation of activity presented in the HierMAP by selecting matrices of a higher level of abstraction (if activity extends upward) or matrices of a lower level of abstraction (if activity extends downward) on the significances network. On the network of personal meanings, the processes of propagation of activity allow the agent to choose the actions that it can make with existing objects, and on the images network to get the sensory data of objects.

2.2 Plan Synthesis Algorithm

Synthesis of the cognitive agent behavior plan is the result of the HierMAP algorithm. The algorithm allows you to build a chain of actions with different levels of abstraction from the initial state to the goal. The planning process begins with the grounding procedure, with the help of which the replenishment of the subject's world model with knowledge of this task takes place. In the grounding procedure, the agent activates signs of objects and subjects, creates a set of rules and substitutions that allow the synthesis of a behavior plan. At the stage of synthesis of the plan, the agent recursively creates all possible plans for reaching the matrix of the goal situation on the network of personal meanings, which describes the goal location of the agent on the map. To do this, the agent searches for a semiotic network from a sign describing the current situation and activates the network elements associated with this sign. Those signs that were received during the spreading of activity “downward» from the situation sign are included in its description (causal matrix), as well as contained in the description (causal matrix) of actions that can be performed in this situation. When extending the activity «upward» from the sign of the current situation, the signs of activity precedents (complex actions) are activated, the performance of which brings the agent much closer to the goal situation than the elementary actions. After activation of the signs of elementary actions, heuristics are applied, which reduce the combinatorial complexity of the algorithm. The heuristic is the procedure in which the signs of actions activate the sign of the next situation, which is compared with the goal situation. The most similar to the goal situation is added to the plan and becomes a new starting point for the activity distribution process.

The described algorithm allows you to save the constructed plan of action as a sign of a complex action (experience) in the agent’s world model. The sign of a complex action contains causal matrices on networks of personal meanings and images, the significances of the sign remain empty. The conditions of the matrix contain a reference to the sign of the initial situation, and the effects refer to the sign of the goal situation. Each of the columns of the conditions of the matrix contains a reference to the sign of the action that is performed at the present plan step (see Fig. 1).

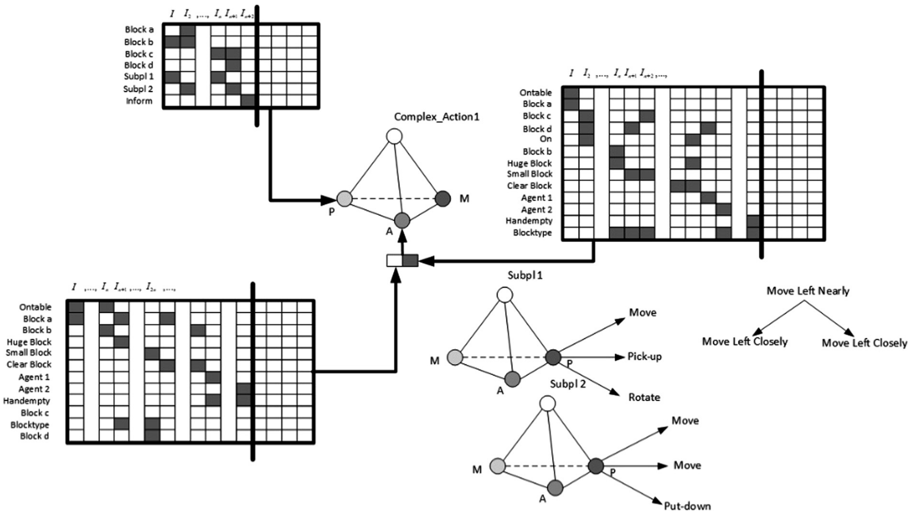

Fig. 1. Complex action’s sign with its causal matrices.

3 Multiagent Knowledge Representation

In the process of activity, the agent may face tasks that cannot be done alone. Situations in which there is a physical limitation of the planning agent (someone can fly, and someone can lift large loads), the lack of sufficient resources to accomplish the goal on their own (battery of the robot, time limit on the task) lead to functional addition of agents to each other, which allows you to optimally solve the problem. Coalition activity of agents requires appropriate multi-agent planning and creation of communication protocols. The spectrum of classical planning problems is significantly expanded due to the need for dynamic re-planning during the plan implementation, the need to consider the redundancy of information about other team members, which in all cases of agent interaction without a coalition contributes to disrupting the activities of other agents for personal gain or the acquisition of additional resources.

In the simplest case, the agents are united in a coalition to achieve the goal. When planning actions in a coalition, an agent must have not only an idea about his capabilities, but also about the capabilities of other members of the coalition. The construction of a multi-agent plan by each of the agents is accompanied by reflexive planning, followed by a joint sampling of a general plan of action. The selection of the general plan of actions by agents is achieved using the methods of reaching agreements such as: auctions [36], contract networks [37] and so on. The plans of each of the agents, as well as in the case of non-group planning, consist of actions of different levels of abstraction, the actions of which can be either specified or not specified plans of other agents. Since coalitions may consist of a heterogeneous set of agents, the synthesis of the plan must consider the role composition of actions and the ability of agents of the current coalition to implement the activities of all the required roles. In many situations, the same action can be performed by different coalition agents, which allows us to talk about the ways to assign roles in coalitions [38].

In the HierMAP algorithm, the sign representation of the agent's knowledge allows one to describe the agent's knowledge of himself with the "I" sign, and the knowledge of other coalition participants as agents of "Agent1", "Agent2". The fact that the agent was aware of the fact "I am here", and everything else "There" made it possible to create an anthropomorphic unified description of all other coalition members using the "They" sign, including references to the signs of other agents in the matrix of personal meanings of this sign. The object representation of other coalition agents provides an opportunity to implement a dynamic process of assigning roles in a coalition, based on the study of precedents of activity. After finding all the available plans, the agents select the most appropriate plan, in the simplest case, based on a set of heuristics:

- Plans of the smallest length are selected.
- Plans are selected with the most uninterrupted sequence of actions by one agent (the communication channel may not be stable).
- Plans are selected with the fewest agents involved.
- Plans are selected in which the planning agent is involved.
- Randomly select one of the remaining plans.

Depending on the number of coalition participants, a meta-action is added to the agent's plan for communicating with other agents. If the coalition includes more than 2 agents, then the procedural matrix on the network of personal meanings of the "Broadcast" sign is activated, otherwise the procedural matrix of the "Notify" sign. The object sign representation of the ways of communication allows not only to activate the corresponding functions of compiling a message adapted for a person and the process of its transmission, but also allows preserving the used method of communication in the experience of the agent. The availability of information about the previous methods of communication of agents provides an opportunity to evaluate the implementation of the plan and change the way of communication with the negative termination of agents' activities.

4 Spatial Logic Representation

Purposeful activity of agents both in a real environment and in a simulation implies the execution of certain actions on the manipulation of environmental objects and on moving around the map. Next, we consider the specific application of the HierMAP algorithm for the problem of smart relocation tasks [39–41].

In the HierMAP algorithm, agents synthesize a plan using a spatial knowledge representation of the environment, which is described by dividing the surrounding space into 9 cells of the agent's attention focus, which dynamically changes its size depending on the presence of surrounding objects and 9 map regions whose dimensions remain static throughout the construction and implementation of the plan by the agent. The focus of the agent and the terrain map is formed using the causal matrixes of the "Location" and "Content" signs, which contain references to the spatial and quantitative relations of the surrounding objects relative to the central cell in which the agent is located. An example of spatial descriptions are the matrices of the signs "Nearly", "Closely" and "Far Away". The semiotic representation of environmental knowledge allows you to create a hierarchy of spatial relationships that are understandable to human. The representation used is consistent with the statement that spatial representations are dependent on the subject matter and scope. For example, if we describe to our friend the distance from the research institute to the nearest metro station within our city, then the entrance to the metro will be far from the institute, and if we describe the same distance, but within the dialogue about the distances between cities and countries, then the distance to the subway becomes insignificant. In addition, the hierarchy of spatial relations is observed by the fact that a relation to a weakly remote point of space is a relation to some close point and the same relation from that close point to a close point from it in the same direction.

5 Experiments

As part of the demonstration of the features of the use of the sign approach in complex problems, an experimental study was presented. The main criterion for the selection of tasks was the presence of subplans in the plans synthesized by agents. The agents-built plans for intellectual movement, which at the elementary level consisted of the actions "pick-up block", "put-down block", "rotate", "move" and "Inform". The domain of the tasks under consideration is a spatial extension of the classical "Blocks world" problem. In the hierarchical case, the set of actions is replenished by the actions "Abstract" and "Clarify", which allow dynamic changes in the dimension of the agent's focus, as well as the case-law actions of movements and previously synthesized plans.

Experiments are made on the PC AMD FX ™ - 6300 Six – Core Processor 3.76 GHz with 16 Gb RAM.

Since the comparison of our algorithm occurred with single-agent algorithms, the following are experiments with a single agent. The differences between these experiments and experiments with a multitude of agents will not be strongly expressed, since each agent in our algorithm is independent and calculates plans at its own facilities. In the framework of this study, only tasks related to planning within the framework of knowledge already existing in the agent's world picture were considered, all plans could be found and no additional acquisition of environmental knowledge by agents was required.

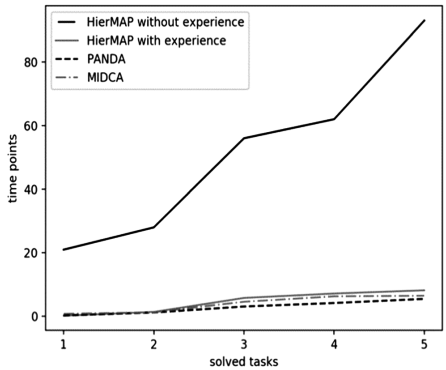

Fig. 2. Comparison with HTN planners.

Figure 2 shows the dependence of the solution time on the number of objects and obstacles in the path of the agent (narrow hallways, transitions, etc.) – black graph and elapsed time when using experience – gray graph. The dotted line denotes the PANDA algorithm, the dash point line denotes the MIDCA algorithm. 5 tasks were considered:

1. Move from one end of the card to another. Detour obstacles in the form of a table.
2. Move from one end of the card to the other. Avoiding multiple obstacles.
3. Departure from the narrow corridor to the large room. The presence of obstacles in the form of a wall.
4. Travel through a narrow corridor and check into a small room. The presence of obstacles in the form of a set of walls.
5. Moving a block from one table to another. Movement with the object.

Methods greatly speed up the planning process, but if there are precedents of activity, the HierMAP algorithm produces a result that does not differ much in time, even considering the fact of much better detail of actions (1 classically defined action for moving in the HTN planner equals from 1 to 12 action to move in HierMAP).

6 Conclusion

The paper presents a psychologically plausible approach to the problem of hierarchical multi-agent behavior planning. An example is given of applying the developed algorithm as a method for calculating an agent's intelligent movement plan, at each step of which an agent can explain his actions to a person. A model example of accelerating the process of synthesizing a plan through the use of activity precedents is given, and a comparison with other hierarchical planning algorithms was also given. In the further work, cases of co-operation of agents and the transfer of entire scenarios of activities will be considered in more detail, and robotic examples for the claimed algorithm will be given.

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