Synthesis of the Behavior Plan for Group of Robots with Sign Based World Model

Gleb A. Kiselev[1] and Aleksandr I. Panov[1,2](✉)

[1] Federal Research Center "Computer Science and Control", Russian Academy of Sciences, Moscow, Russia
{kiselev,pan}@isa.ru

[2] National Research University Higher School of Economics, Moscow, Russia

Abstract. The paper considers the task of the group's collective plan intellectual agents. Robotic systems are considered as agents, possessing a manipulator and acting with objects in a determined external environment. The MultiMAP planning algorithm proposed in the article is hierarchical. It is iterative and based on the original sign representation of knowledge about objects and processes, agents knowledge about themselfs and about other members of the group. For distribution actions between agents in general plan signs "*I*" and "*Other*" ("*They*") are used. In conclusion, the results of experiments in the model problem "Blocksworld" for a group of several agents are presented.

Keywords: Multiagent planning · Sign · Behavior planning · Task planning · Robots · Group of robots · Sign based world model

1 Introduction

Collective robotics mind currently attract attention of specialists in artificial intelligence (AI), as well as experts in the actual robotics. Great success has been achieved in team games (i.e. RoboCup [10]) and joint movement of unmanned vehicles (swarms and UAV groups) [7,8,19]. However, the task of allocating roles in a group of autonomous agents that solve more than one of the specific problem, is universal, i.e. able to learn in the new stating the statements and simultaneously taking into account the opportunities and training of others agents that are integral parts of the solution was much more complicated and good-enough solution still does not appear. The main efforts to solve this problem of robotic system that would allow it not only to function sport, but also to learn in it, to build conceptual plans of behavior and exchange messages with other members of the coalition [2,6,18]. One of the key the subtask in creating such cognitive resources is the selection and use of method of knowledge representation and the basis for the synthesis behavior plan.

In this paper we present the original MultiMAP algorithm - behavior plan synthesis of a group of intelligent agents that represent robotic systems with different manipulators, which constrain their ability to interact with objects of

A. Ronzhin et al. (Eds.): ICR 2017, LNAI 10459, pp. 83–94, 2017.
DOI: 10.1007/978-3-319-66471-2_10

the external environment. For example, some agents can operate only with big objects and others only with small ones. Such a difference in functionality leads to the fact that some tasks can not be solved only by one agent and encourage him to consider the possible actions of other agents. To represent knowledge about processes and objects of the external environment, knowledge about himself and other agents in real work uses a model of sign based world model [13–15], which relies on the psychological theory of human activity [9,11]. The base element of sign world model is a four-component structure - a sign that combines both declarative and procedural knowledge about the object, process or subject activities. The agent keeps the idea of himself and his abilities in the sign "I", and information about the abilities of other agents - in the corresponding signs "A_1", "A_2", etc.

The proposed planning algorithm is iterative and hierarchical. Convergence of the iterations of planning from the declared event case, if the knowledge or skills of the agent is enough to build a complete plan. Hierarchy is that conceptual actions the agent at the beginning tries to use, specifying them if necessary. The model of sign based world model allows an agent to include in the plan both his own actions and the actions of other agents. Also, the agent remembers all his successful attempts to achieve goals and subgoals, using the accumulated experience in new situations, which allows planning on the precedents, the decreasing time, the execution of the plan and the length of the resulting chains of actions.

The paper is organized as follows. In Sect. 2 complete the statement of the planning in a group of intelligent agents problem and a short description of the presentation tasks for agents (ML-PDDL and PDDL3). In Sect. 3 a brief overview of the planning in multi-agent systems and comparison with the present work. In Sect. 4 presented implementation of algorithm in the group of agents possessing the sign based world model, and a description of the model problem "Blocksworld" is given. In Sect. 5 the results of model experiments and their discussion are given.

2 Problem Statement

In this work, an intelligent agent will be understood as hardware or a software system that has the autonomy, reactivity, activity, and commutativity properties. These properties allow the agent to interact with the environment that includes various types of objects. The plan P of the agent A_k is called the sequence of actions $P(A_k) = \langle a_1(A_{i1}), a_2(A_{i2}), \ldots \rangle$, obtained as a result of planning algorithm work, where A_{ij} is the agent performing the action a_j. The plan is formed by agent based on the goal, information about the current state of the environment and the dynamics of its change. In the present paper we consider the simplest case where agents modelling plans in tasks which have only the one possible choice of the roles distribution. This allows us not to consider the problems of coordinating plans.

We describe the task and the planning domain using languages PDDL3 and ML-PDDL [3], which uses the predicate calculus of the first order. The planning task $T = \langle AO, S, F, C\rangle$ consists of a set of agents and objects of the environment OE (example in Table 1 - field: objects), initial S and final F states of the environment (fields *:init* and *:goal*) and the constraints on the actions of agents C (field *:constraints*). The initial state S consists of a predicates set which are true in the initial situation, before the action is initiated by the agent, F includes the predicates that are true in the goal situation of the problem. The set C describes the constraints on the applicability of an action in the context of agent properties. For example, agent A_1 only works with small objects, and A_2 only with big ones.

The domain of the problem $D = \langle V, TO, A\rangle$ includes descriptions of predicates V, types of TO objects, and actions of agents A. The type of objects defines a class-subclass relation in the agent's knowledge base. Predicates describe some statement about an object (for example, a predicate $\langle blocksize\rangle$: a big block). The planning domain includes non-specific predicates that describe the type of relationship between an object of a certain type and its specific property. The planning task includes the specified predicates, where an abstract type of substituted coefficients is found. The description of the action $a = \langle n, Cond, Eff\rangle$includes the name of the action n, a list of its $Cond$ preconditions and Eff effects. The list of preconditions includes predicates that form the condition for applying this action, and the effect listings consists of predicates, which meanings became true after applying the action. The effect also includes a set of predicates with the NOT key, which denote those predicates whose meaning has ceased to be true.

In the article the task is transformed from the description presented in PDDL to a sign based world model. The loading the world model process of an agent is explicitly described in Sect. 4.2.

3 Related Works

Planning in a group of agents is a sufficiently developed direction in the theory of multi-agent systems. We note a number of papers using a close formulation of the problem.

In the article [5] the approach directed on improvement of productivity of agents in successive manipulation problems is considered. A disconnected with the agent optimization-based approach to problem solving planning and motion adjustment is described, including elements of symbolic and geometric approaches. The algorithm generates auxiliary actions of the agent, which allows other participants to reduce cognitive and kinematic load during the task execution being in the coalition of agents. The task domain is described using symbolic predicates with the addition of special functions to implement geometric constraints in the algorithm. The target state is described by abstract predicates, which make it possible to indistinctly represent individual components. Tasks of this type can be solved using the MultiMAP scheduling algorithm described in this paper, personalizing the process constructing a plan by using knowledge about the current preferences of each of the team member and made by each one.

Table 1. Example of domain description and planning task

Planning domain	Planning task
(define (domain domain-name)	(define (problem BLOCKS-4-0)
(:requirements :typing :multi-agent)	(:domain blocks)
(:types	(:objects
agent object1 - object	a - object1
)	b - object1
(:predicates	ag1 agent
(predicate-1 ?ob1 object1 ?ag agent)	ag2 - agent)
(predicate-2 ?ob1 object1)	(:init
(predicate-3 ?ag agent))	(predicate-1 a ag1)
(:action action-name	(predicate-1 b ag2))
:parameters (?ob1 object1 ?ag agent)	(:goal
:precondition (and	(and
predicate-1 ?ob1 ?ag))	(predicate-2 a)
:effect (and	(predicate-3 ag1)
(not (predicate-1 ?ob1 ?ag))	(predicate-2 b)
(predicate-2 ?ob1)	(predicate-3 ag2))))
(predicate-3 ?ag agent)))	(:constraints
	(and
	(and (always (forall (?ob1 - object1)
	(implies (predicate-2 ?a) (predicate-1 ?
	x ?ag1)))))

The article [12] considers a multi-agent approach to the use of the LAMA planning algorithm [20]. The planning algorithm described in the article builds plans of various levels, where the plan of the highest level consists only of public actions of agents. Each public action is interpreted by the agent as a private action plan based on facts internal to the agent. A high-level plan is considered to be valid if each agent draws up an action plan independently from other agents until the private preconditions for public action are reached, which he performs in a high-level plan. The means of representing knowledge in the article is the logic of the predicate calculus of the first order.

The article [1] describes the algorithms of weak and strong privacy, created to realize the possibility of hiding personal actions that make up the process of performing a public action within the framework of a multi-agent approach to the construction of team of agents action plan. To describe the domain and the planning task, a multi-agent version of the PDDL language is used, which allows manipulating with private actions and facts. In this paper, each of the agents plans make actions within their own world map processes, which implies the use of private, personal agent actions. However, the notions of limitations of possible actions of other agents are part of the picture of the world of the planning agent, which he created on the basis of available data on other agents.

4 Method and MultiMAP Algorithm

4.1 Sign Based World Model

In this paper the model of the sign based world model is used as the main way of knowledge representation, the basic element of which is a four-component structure, called the sign [14,16]. The sign can represent both a static object and an action. The sign is given by the name and contains the components of the image, significance, and personal meaning. The image component contains the characteristic features of the represented object or process. The significance component represents generalized usage scenarios for the collective of agents. The component of the personal meaning of the sign determines the role of the object in the actions of the subject committed by him with this object. Personal meanings of the sign are formed in the process of the subject's activity and are the concretization of scenarios from the meaning of this sign. Personal meanings reveal the preferences of the subject of activity, reflect the motive and emotional coloring of the actions.

The components of the sign consist of special semantic (causal) networks at the nodes of which the so-called causal matrices are located. Each causal matrix represents a sequence of lists (columns) of attributes of a given sign component. The attributes are either elementary data from sensors or references to the corresponding signs. For example, the causal matrix of the sign *on* consists of two columns: the left column contains the sign of the $blockX$, and the right sign the $blockY$, which indicates that the $blockX$ is *on* the $blockY$. Using each of the three resulting causal networks, it is possible to describe a series of semantic relations on a set of signs. So among the relations on a set of signs on a network of significance there is a class-subclass relation, when for one sign designating some role there can be several signs playing this role, forming its causal matrix on a network of significance.

Formally, the s symbol is a tuple of four components: $\langle n, p, m, a\rangle$, where is the name of the sign, p is the image of the sign corresponding to the node $w_p(s)$ of the causal network on the images, m is the sign significance corresponding to the node $w_m(s)$ of the causal network of significances, a - the personal meaning of the sign, corresponding to the node $w_a(s)$ of the causal network on the senses. R_n - relations on the set of signs, and θ - operations on the set of signs, obtained on the basis of fragments of causal networks, to which the corresponding sign components belong. A tuple of five elements $\langle W_p(s), W_m(s), W_a(s), R_n, \theta\rangle$ is a model of a semiotic network.

The model of the sign based world model is used in this paper as the basic way of representing knowledge for building collective plans. As part of the process of plan finding in a sign based world model, the reverse planning process (from the target situation) is carried out, described in detail in Sect. 4.2. Agents perform various actions based on their personal meanings and try to reach the initial situation. Knowledge of the capabilities of the planning agent and other agents is represented by nodes on the causal networks of the personal meanings of the sign "I" and the signs "A_1", "A_2" etc. for each agent, respectively, which allows agents to plan their actions based on the criteria for the possibility of applying actions by the planning agent, or from the possibility of applying the actions of someone from other agents of the group. Like any sign, the causal matrix of sign "*I*" consists of the personal meanings of the agent, carrying out the planning process, its image and significances. The image of the agent and other members of the group is his main characteristic, important for the recognition of other agents by sensor data, so we have omitted this component. The significance of the "*I*" sign and the signs of other agents are generalized scenarios (actions) in which an agent can act as an entity either directly or through its classes. All actions that agent A_i can perform are represented in his personal meanings and are partially specified value whose action roles are prefilled in accordance with the block of constraints $C(A_i)$ presented in the planning task T.

The signs of other agents are related by a class-subclass relationship to the abstract sign "*They*". Agent signs include agent views of the remaining agents, derived from a general description of the planning task.

4.2 MultiMAP Algorithm

The planning process in the sign based world model is realized with MAP-algorithm [17,19] and goes in the opposite direction: from the final situation to the initial one. The input of the algorithm is a description of the task $T_{agent} = \langle N_T, S, Sit_start, Sit_goal \rangle$ where N_T - the task identifier, S - the set of signs, including the sign of the current agent S_I, and the signs of other agents $S_{Ag1}, S_{Ag2}, S_{Ag3}, \ldots$. $Sit_{start} = \langle \emptyset, \emptyset, a_{start} \rangle$ - the initial situation is modeled by a sign with meaning $a_{start} = \{z^a{}_{start}\}$, $Sit_{goal} = \langle \emptyset, \emptyset, a_{goal} \rangle$ - the target situation with meaning $a_{goal} = \{z^a{}_{goal}\}$.

Input: description of the planning domain D, description of the planning task T
maximum depth of iterations i_{max}
Output: *plan*

```
For agent in agents:
  T_agent := GROUND(P, A)
  Plan := MAPSEARCH(T_agent)
function MAPSEARCH(T_agent)
  z_cur := z^a_goal
  z_start := z^a_start
  Plans := MAPITERATION(z_cur, z_start, ∅, 0)
  {Plan_0, Plan_1, ...} = SORT(PLANS)
  return Plan_0
function MAPITERATION(z_cur, z_start, Plan_cur, i)
  if i > i_max then:
    return ∅
  Act_chains = getsitsigns(z_cur)
  for chain in Act_chains:
  Act_signif = getactions(chain)
  for pm_signif in Act_signif:
    Ch = openaction(pm_signif)
meanings = generatemeanings(Ch, agents)
  checked = activity(z_cur, meanings)
  candidates = metaactivity(checked)
  for candidate, agent in candidates:
    z_cur+1 = timeshiftbackwords(z_cur,
                    candidate)
    plan.append(candidate, agent)
    if z_cur+1 ∈ z_start:
      return plan
  else: Plans := MAPITERATION(z_cur+1,
                    z_start, plan, i + 1)
```

The algorithm begins with the process of symbol grounding (loading the sign based world model of the agent) GROUND, in which corresponding signs and relations are created for all objects, roles, predicates and actions in them in the causal networks of significances and personal meanings. For the initial and final situations, the signs Sit_{start} and Sit_{goal} are created and nodes of causal networks of personal meanings $w_a(Sit_{start})$ and $w_a(Sit_{goal})$ are defined. In general, the T_s task is the result of the symbol grounding procedure - the formation of world model from the original descriptions of the planning domain D and the planning task T.

The result of the implementation of the MultiMAP algorithm is a plan $Plan = \{\langle z^a_{s1}, z^a_{p1}, S_x\rangle, \langle z^a_{s2}, z^a_{p2}, S_x\rangle, \ldots, \langle z^a_{sn}, z^a_{pn}, S_x\rangle\}$ - sequence of the length of n pairs $\langle z^a_{si}, z^a_{pi}, S_x\rangle$, where z^a_{si} is the causal matrix of a certain network node on the personal meanings representing the i planning situation, z^a_{pi} - the causal matrix of some personal meaning representing the action applied in the z^a_{si} situation, and S_x the agent sign, $x \in \{I, Ag_1, Ag_2, Ag_3, \ldots\}$ depending on the possibility actions by the agent himself or by other agents. In this case, the situation z^a_{si+1} is the result of the action z^a_{pi}, in the sense that is revealed later in the discussion of the algorithm, $z^a_{s1} := z^a_{start}$ - the causal matrix, corresponding to the meaning of the initial situation, $z^a_{sn} := z^a_{goal}$ - the causal matrix corresponding to the meaning of the target situation.

For each agent, the planning algorithm starts with the process of signification. In this process, signs are generated from the data received by the agent through domain analysis and planning tasks. The process of signification is the process of creating a of the subject's world model, within the framework of this process, the networks of significances and personal meanings of the agent are formed from causal matrixes of signs, signs "*I*" and "*They*" are formed.

The process of signification begins with the creation of signs of agents and objects and with the creation of corresponding causal matrices on a network of significances. After this, signs and causal matrices of object types are created, procedural signs for predicates and actions. There is a formation of class-subclass relations between different object signs. In the causal matrix on the network of personal meanings of the sign "I" includes the sign of the agent performing the planning process, the signs of other agents are included in the causal matrix of the sign "They". Procedural and object signs that satisfy the constraints of agents are included in causal matrices on the network of personal meanings of the agent's sign. In the causal matrix on the network of personal meanings of the sign "I" are included constraints related to the activities of the planning agent, with respect to the available for use object and procedural signs. Causal matrices are created on the network of personal meanings of the signs of the initial and final situation, the corresponding object signs are included in them.

Steps 4–26 describe an algorithm for constructing an action plan for each of the agents. After this, the $MAPITERATION$ function described in clauses 10–26 is executed. At the first step of the recursively called $MAPITERATION$ function, the current recursion step is compared with the maximum iteration step i_{max} - if it is exceeded, the function returns an empty set. In step 13, all the characters appearing in the description of the current situation (*getsitsigns*) are received. In step 15 - the generation of all procedural marks (*getactions*), in step 17, a list of all object signs included in the causal matrices of procedural signs (*openaction*) is created. In steps 18–20, new nodes of the causal network of the personal senses of procedural signs are searched for, into the causal matrices of which the signs of the target situation enter. From point 21 to point 26, the process of creating a new situation occurs on the basis of the signs entering into the causal matrices of the received procedural signs and signs entering into the causal matrix of the current situation. In step 26, a recursive call to the

$MAPITERATION$ function occurs if the new causal matrix created in step 22 is not included in the initial situation matrix, otherwise, the function returns the found plans.

4.3 Model Example

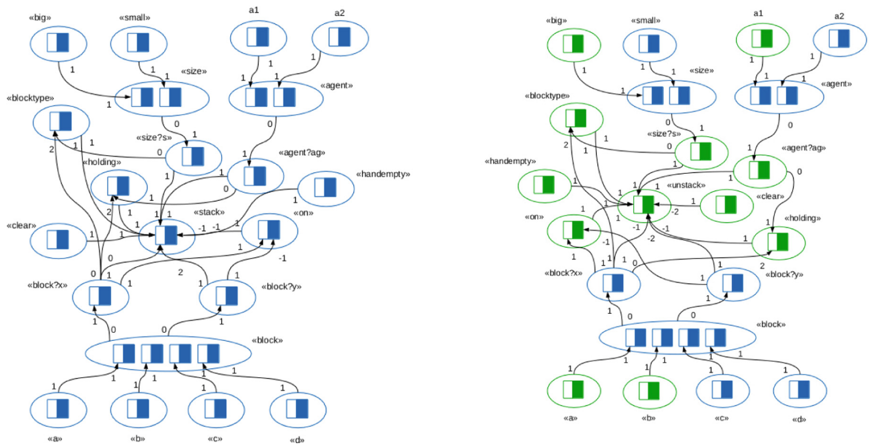
An example of work of the presented algorithm can be the solution of planning task in the well-known formulation of the "Blocksworld" [4] task. Problem domain is described in the multi-agent version of the PDDL language and serves as the initial data for the formation of the sign based world model. World model consist of object signs such as the sign of the "*block*" and procedural signs "*on*", "*holding*", "*pick-up*", "*unstack*", etc. The agent is specified by a special object with type agent. Blocks have different sizes (predicate "*size*"), and agents are available action "*wait*", which contain empty sets of conditions and effects.

Here is an example of a MultiMAP planning algorithm solving a problem in which, in the initial situation, the four blocks "*a*", "*b*", "*c*" and "*d*" are on the table, the signs of each of these block includes in the causal matrix of the "*ontable*" sign, the block "*a*" and "*c*" are big, that is, the sign "*size*" is replaced by the sign "*big*" when forming the causal matrix of the procedural sign "*blocktype*" using the signs of these blocks in the process of signification, while the other two blocks are small and the sign "*size*" is replaced by the sign "*small*". Two agents that operate with different types of blocks have empty manipulators and blocks are clear, that is, the signs of the blocks are included the causal matrices of the personal meaning of the sign "*clear*". The result of solving this planning task are plans of each of the agents for the construction of the tower "*a-b-c-d*", in which the sign of the block "*d*" is included the causal matrix of the procedural sign "*ontable*", the causal matrix of the sign "*clear*" includes the sign of the block "*a*", and the remaining signs form causal matrices of the procedural sign "*on*". For each agent in the causal matrix, on a network of personal meanings includes procedural and object signs that satisfy the constraints of the problem.

In Fig. 1 shows a fragment of the causal matrix on the significance network of the procedural sign "*stack*". A similar network displays a sequence of class-subclass relations and a role-sign relations for each of the action objects in the MAP-planning algorithm. Thus, the sign "*block?x*" during the formation of the causal matrix of procedural signs is replaced by the sign of any of the blocks, which does not contradict the constraints of the problem described in the set C.

At the first stage of the main iteration of the algorithm, set of precedents are obtained, empty in the simplest case. At the next stage, the process of obtaining object signs included in the current situation and defining the procedural signs "*stack*", "*unstack*", "*put-down*", "*pick-up*" and "*wait*".

Next, the formation of causal matrices of procedural signs occurs by replacing the signs of roles with object signs, in Fig. 1 shows the process of constructing the matrix of the procedural sign "*unstack*" from the object sign "*a*". At this stage, the applicability of the resulting causal matrices of the procedural signs is checked by screening out those causal matrices that do not fit the constraints of the problem, or do not satisfy the selection heuristic. Constraints of the task are related to the possibility of applying the actions of the agent, which are described by the presence of appropriate procedural and object signs in the causal matrix on the network of personal meanings of the agent's sign. In Fig. 1, the causal matrices that are involved in the formation of the causal matrix on the network of personal meanings of the procedural sign "*unstack*" are highlighted in green, under the condition that the signs "*a*" and "*b* are included in the required causal matrix. Since the block "*a*" is big by the condition of the problem (the object sign "*a*" included in the causal matrix of the significances of the procedural sign "*blocktype*" along with the object sign "*big*"), taking into account the constraints of the problem, only the agent "A_1" can perform manipulations with it.



Causal matrix of the procedural sign "*stack*" on significance network

The process of obtaining the sign of the procedural matrix of the "*unstack*" action

Fig. 1. Network representations of actions "*stack*" and "*unstack*"

At the final stage of the iteration, a new causal matrix z_{next} is created on the network of personal meanings, representing the following planning situation. As a result of the algorithm, plans are created by each of the agents:

$$A_1 : (pick - upc, I), (stackcd, I), (pick - upb, A_2), (stackbc, A_2), (pick - upa, I), (stackab, I).$$

$$A_2 : (pick - upc, A_1), (stackcd, A_1), (pick - upb, I), (stackbc, I), (pick - upa, A_1), (stackab, A_1).$$

5 Experiments

Within the model problem presented in Sect. 4.3, experiments were performed describing the problems solved by the MultiMAP planning algorithm. The results of experiments are described in Table 2.

Based on the obtained data, the graphs of memory usage and time spent were constructed depending on the complexity of the tasks (Fig. 2).

Table 2. Results of the conducted experiments with the MAP-algorithm in the context of solving the problems of the "Blocksworld" task (WM - sign based world model)

#	Amount of agents	Amount of blocks (task complexity)	Plans length	Amount of signs in agents WM	Plans time counting	Amount of memory for each plan
1	2	4	6	29	9.189	34.8
2	2	5	8	30	20.153	46.5
3	3	5	8	32	61.627	83.4
4	3	6	10	33	114.927	130.6
5	3	8	14	35	321.948	307.6
6	4	8	14	37	731.760	503.1
7	3	4	8	29	15.343	143.1
8	3	4	8	29	7.842	49.7

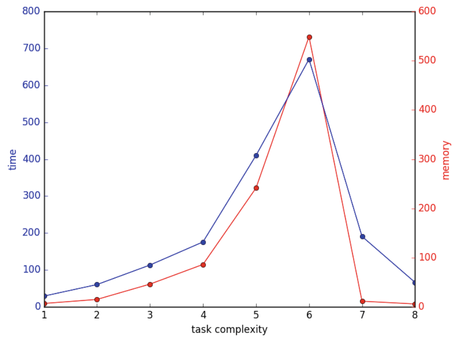


Fig. 2. Graphs of the dependence of the memory used and the timing of the plans processing relative to the complexity of the problem. "*a*"

According to the data shown in Fig. 2, it can be concluded that with an increase in the number of subjects and objects in the planning algorithm, there is a fairly strong increase in resource consumption, which complicates the process of cognitive evaluation of the complex situation for a large number of stakeholders. Despite the fact of the length and laboriousness of calculations, the pre-constructed action plan at times facilitates the tactical operation of the agent, providing possible auxiliary actions of other agents. A sing approach to planning provides an opportunity to preserve the experience accumulated in the process of acting agents, greatly accelerating the process of finding plans for solving similar problems which becomes obvious from the data of 7 and 8 experiments. Experiment 7 uses a task with similar objects, agents, and constraints with task 1, but the initial situation has been partially changed. In the 8th experiment, the experience of the agents is used in finding the plan in the first problem for finding the plans in the general problem with the 7th experiment.

6 Conclusion

The paper presents an algorithm for planning behavior by an intelligent agent with based on signs world model and functioning in a group of heterogeneous agents. The agent is given the task of achieving a certain goal in the space of conditions of the environment, which he is unable to achieve independently. In the sign based world model agents are described by signs "*I*" and "*Other*" ("*They*"), which allow them to include both their actions in the plan, and the actions of others. The proposed MultiMAP algorithm was tested on the model task "*Blocksworld*". In the future, it is planned to enable agents to assess the possible costs of performing actions and choose between different, both group and individual plans, for the least use of the resource. Also, to compile and select more complex plans, special sign protocols of communication between agents will be developed.

Acknowledgments. This work was supported by the Russian Science Foundation (Project No. 16-11-00048).

References

1. Brafman, R.I.: A privacy preserving algorithm for multi-agent planning and search. In: Proceedings of the Twenty-Fourth International Joint Conference on Artificial Intelligence (IJCAI 2015), pp. 1530–1536 (2015)
2. Emel'yanov, S., Makarov, D., Panov, A.I., Yakovlev, K.: Multilayer cognitive architecture for UAV control. Cogn. Syst. Res. **39**, 58–72 (2016)
3. Gerevini, A.E., Long, D.: Plan constraints and preferences in PDDL3. Technical report (2005)
4. Gupta, N., Nau, D.S.: On the complexity of blocks-world planning. Artif. Intell. **56**(2–3), 223–254 (1992)
5. Hayes, B., Scassellati, B.: Effective robot teammate behaviors for supporting sequential manipulation tasks. In: International Conference on Intelligent Robots and Systems, pp. 6374–6380 (2015)
6. Hélie, S., Sun, R.: Autonomous learning in psychologically-oriented cognitive architectures: a survey. New Ideas Psychol. **34**(1), 37–55 (2014)
7. Hexmoor, H., Eluru, S., Sabaa, H.: Plan sharing: showcasing coordinated UAV formation flight. Informatica (Ljubljana) **30**(2), 183–192 (2006)
8. Ivanov, D., Kalyaev, I., Kapustyan, S.: Formation task in a group of quadrotors. In: Kim, J.-H., Yang, W., Jo, J., Sincak, P., Myung, H. (eds.) Robot Intelligence Technology and Applications 3. AISC, vol. 345, pp. 183–191. Springer, Cham (2015). doi:10.1007/978-3-319-16841-8_18
9. Kahneman, D.: Thinking Fast and Slow. Penguin, New York (2011)
10. Kitano, H., Asada, M., Kuniyoshi, Y., Noda, I., Osawai, E., Matsubara, H.: RoboCup: a challenge problem for AI and robotics. In: Kitano, H. (ed.) RoboCup 1997. LNCS, vol. 1395, pp. 1–19. Springer, Heidelberg (1998). doi:10.1007/3-540-64473-3_46
11. Leontyev, A.N.: The Development of Mind. Erythros Press and Media, Kettering (2009)

12. Maliah, S., Shani, G., Stern, R.: Collaborative privacy preserving multi-agent planning. Auton. Agents Multi-Agent Syst. **31**(3), 493–530 (2017)
13. Osipov, G.S.: Sign-based representation and word model of actor. In: Yager, R., Sgurev, V., Hadjiski, M., Jotsov, V. (eds.) 2016 IEEE 8th International Conference on Intelligent Systems (IS), pp. 22–26. IEEE (2016)
14. Osipov, G.S., Panov, A.I., Chudova, N.V.: Behavior control as a function of consciousness. I. World model and goal setting. J. Comput. Syst. Sci. Int. **53**(4), 517–529 (2014)
15. Osipov, G.S., Panov, A.I., Chudova, N.V.: Behavior control as a function of consciousness. II. Synthesis of a behavior plan. J. Comput. Syst. Sci. Int. **54**(6), 882–896 (2015)
16. Osipov, G.S.: Signs-based vs. symbolic models. In: Sidorov, G., Galicia-Haro, S.N. (eds.) MICAI 2015. LNCS, vol. 9413, pp. 3–11. Springer, Cham (2015). doi:10.1007/978-3-319-27060-9_1
17. Panov, A.I.: Behavior planning of intelligent agent with sign world model. Biol. Inspired Cogn. Archit. **19**, 21–31 (2017)
18. Panov, A.I., Yakovlev, K.: Behavior and path planning for the coalition of cognitive robots in smart relocation tasks. In: Kim, J.-H., Karray, F., Jo, J., Sincak, P., Myung, H. (eds.) Robot Intelligence Technology and Applications 4. AISC, vol. 447, pp. 3–20. Springer, Cham (2017). doi:10.1007/978-3-319-31293-4_1
19. Panov, A.I., Yakovlev, K.S.: Psychologically inspired planning method for smart relocation task. Proc. Comput. Sci. **88**, 115–124 (2016)
20. Richter, S., Westphal, M.: The LAMA planner: guiding cost-based anytime planning with landmarks. J. Artif. Intell. Res. **39**, 127–177 (2010)