Models of Robots Teams Behavior

Alexander Kulinich

V.A. Trapeznikov Institute of Control Sciences RAS, Profsoyuznaya 65, Moscow, 117997, Russia

Abstract

The work considers command behavior models of reactive robots and intelligent robots with quality BDI architecture. For reactive robots, the principles of the formation of spontaneous teams based on the principles of the social organization of people are determined. The architecture of an intelligent robot with qualitative BDI architecture is proposed. For intelligent robots, behavioral planning models are proposed, and the conditions for their cooperation are formulated. The proposed principles for the formation of reactive robots teams and the conditions for the cooperation of intelligent robots were investigated in the simulation of the mechanisms of formation and functioning of robot teams.

Keywords

Reactive robot, flock, team, intelligent robot, behavior, society

1. Introduction

Currently, a promising area of group robotics is the creation of groups of sets of simple robots capable of solving complex problems through self-organization.

Algorithms for the behavior of a robot's group, based on the local interaction of sets of homogeneous reactive robots, provide their coordinated movement, avoid obstacles, and are based on the principles that formalize the movement of birds' flocks [1].

In the scientific literature, there are many publications on the implementation of swarm and flock algorithms robots behavior for solving various problems. For example, in [2], 40 algorithms are given that implement the most diverse movement of reactive robots groups. In [3], various algorithms for avoiding obstacles by a flock (swarm) of agents and collision avoidance are investigated.

In addition to the tasks of moving a robot's group in formation, in group robotics there are several typical tasks - these are tasks of patrolling the territory, foraging, mapping, etc. [4]. To solve such problems, the principles of robots movement in the Reynolds system are insufficient.

The search for principles of behavior of a robot's group that would provide a solution to a specific general complex problem, in general, is not a trivial task. As such principles, the principles of behavior of insects, animals, or humans can be chosen.

The transfer of the behavior principles of insects or humans to the behavior of artificial robots requires the expansion of the capabilities of reactive robots, to the capabilities of intelligent robots with cognitive capabilities. The robots' cognitive capabilities are understood as the appearance of their cognitive properties: perception; beliefs; preferences, etc.

The architecture that allows realizing the properties of intelligent robots is a mental BDI (Belief-Desire-Intention) architecture, in which the following elements are defined: Beliefs characterize the robots' knowledge of the subject area; Desires reflect the goals of robots and Intentions are the possible actions of robots to achieve their goals [5].

The task of creating a robots team with BDI architecture is to organize the information exchange about their mental states between robots. We are talking about the robots' self-organization in a

Proceedings Integrated Models and Soft Computing in Artificial Intelligence (IMSC-2021), 17-20 May, 2021, Kolomna, Russia
EMAIL: alexkul@rambler.ru
ORCID: 0000-0002-4751-205X

dynamic process, which is based on the information exchange by agents about their mental states, for robots to achieve a common goal without external interference.

The issues of team behavior of intelligent agents (robots) with BDI architecture were studied in [6]. In these studies, the principles (specifications) of organizing the joint work of a group of agents are introduced based on the common intentions of the agents. In the theory of general plans [7], the main basic concept is the group plan. To complete the group plan, agents must agree on the actions they will take to implement the group plan.

Interest in modeling the collective behavior of simple reactive agents appeared in the 60s of the last century. So, in the works [8], [9], based on the study of the collective behavior of finite automata, the theoretical foundations of the collective interaction of agents were laid.

The formation of teams (coalitions) of agents is studied within the framework of the theory of cooperative games [10]. Here the problem is solved under the condition of the agents’ rationality and full awareness of all agents about the goals, resources, and strategies of other agents.

However, while ensuring full awareness of agents, the implementation of this approach has an exponential complexity of calculations and communications between agents to their number, which limits the possibility of its practical application [11].

Interesting are the methods based on modeling the agents' behavior in the coalition's formation based on the theories of social choice and social dependence [12]. These methods make it possible to quickly solve the issues of forming open dynamic coalitions, the composition of which can change in the process of solving the problem, and the agents can freely enter or leave the coalition.

Intelligent Agent Research Associations: Foundation for Intelligent Physical Agents (FIPA), Object Management Group (OMG) has developed and standardized languages and protocols for knowledge representation and information exchange. For example, the language and protocol for the exchange of information and knowledge KQML, presentation and knowledge exchange languages (KIF, RDF, OWL), agent communication language (ACL - FIPA).

Thus, there is a theoretical and technological basis for the development of multi-agent systems that solve group problems, which can be easily transferred to the conceptual level of robots group behavior. However, many conceptual issues related to the organization of team behavior of BDI agents, for example, in uncertain conditions based on the social behavior principles, require additional research.

This paper investigates models of command behavior of reactive robots and intelligent robots with a qualitative BDI architecture, based on heuristic models of social behavior.

2. Spontaneous teams of reactive robots

In [4], algorithms of robot flock behavior were considered, which assumed the information exchange between robots about their own goals and resources. In this work, principles of behavior of spontaneous teams of reactive robots are proposed for foraging tasks that do not involve the exchange of information. The behavior of robots is formulated in the form of principles based on the analysis of the functioning environment state and their own goals and resources and heuristics of the behavior of robots in conditions of uncertainty.

2.1. The functioning environment model of reactive robots

We will rely on the mathematical formulation of group control in a dynamic system "robots group -environment" [13]. Consider a robots set $A=\{R_i\}$ with properties (parameters) $F=\{f_i\}$. For each property of each robot, an ordered set of their possible values is defined, $Z=\{Z_i\}$, where $Z_i=\{z_{i1},\dots z_{iq}\}$, $z_{iq+1} \succ z_{iq}$, $q=0\dots n$-1. In addition, a set of objects $B=\{b_j\}$ is defined, each of which has properties from the set Z of properties of robots.

The robot functioning environment is defined as a direct product of the sets of values of all properties of robots, $SF=\underset{i}{\times} Z_i$.

The vector of values of all robots properties and properties of all objects $Y(t) = (Y_1(t),\dots, Y_n(t),\dots, Y_{b1}(t),\dots, Y_{bm}(t))$ determines the functioning environment state, where $Y_1(t)$, $Y_n(t)$ - properties of the *i-th* robot; $Y_{b1}(t), Y_{bm}(t)$ - properties of objects; $Y_i(t)=(z_{1j}, \dots, z_{nb}), z_{ij} \in Z_i, \forall i$..

A change in the functioning environment state occurs when robots change their properties and is presented as a mapping:

$$W{:}Y(t) \rightarrow Y(t+1),$$

where W is the rules system for the robot's behavior, specified on the set of possible states of the environment $W\colon \underset{i}{\times} Z_i \rightarrow \underset{i}{\times} Z_i$; $Y(t)$, $Y(t+1)$ - states of the environment at times t.

Each robot is characterized by the following tuple [4]:

$$\langle g_q,\ r_q,\ \mu_q(Y_q, g_q),\ O(r_q)\rangle,$$

where:

1. $g_q = (z_{1j}^{g}, \dots, z_{nb}^{g})$ is the vector of target values of the robot q, where $g_q \in SF$;
2. $r_q = (z_{1j}^{r}, \dots, z_{nb}^{r})$ is the strategy for achieving the robot's goal q, where $r_q \in U_q$, $U_q = \underset{i}{\times} Z_i^r$, $Z_i^r \subseteq Z_i$ are the resources of the robot q. Robot q is considered to apply the r_q strategy to achieve its goal g_q, assuming that other robots are idle.
3. $\mu_q(Y_q(n), g_q)$ - the ability of the robot q to reach the target state g_q at the expense of its own resources. The possibility of achieving the goal is defined as the proximity of the predicted $Y_q(n)$ and the target situation g_q of the robot:

$$\mu_q(Y_q(n), g_q) = \rho(Y_q(n), g_q)^{-1}.$$

where $\rho(a, b), a,b \in \underset{i}{\times} Z_i$ is a metric defined in the state space. This metric measures the potential "strength" of each robot without the support of other robots.

4) $O(r_q)$ is the usefulness of the target situation for the robot q. The usefulness of the target situation for the robot is understood here as a parameter characterizing the rationality of the robot's behavior in the process of achieving the goal.

The task is to change the functioning environment state from the current $Y(t)$ to the target $Y^*(n)$ by changing the intrinsic properties of robots and the foraging object's properties.

It is believed that knowing the functioning environment state $Y(t)$, the robot, using the resources r_q, tries to achieve its goal g_q on its own, realizing the possibility $\mu_q(Y_q(n), g_q)$ and the utility $O(r_q)$ of achieving the goal.

For the tasks of group robotics, the principles of social behavior of insects, animals, or people are chosen as the principles of robots' team behavior.

2.2. Principles and heuristics of the functioning of spontaneous teams of reactive robots

A spontaneous team of reactive robots is understood as a set of robots that have a common goal, the ability to observe the states of the functioning environment and are unable to communicate with other robots, coordinate their actions, and build a common plan.

By the principle of the formation and functioning of a robot's team, we mean the rules of behavior of each robot based on the analysis of the functioning environment, the information available to the robot about its state, and some heuristics.

Based on the works of social psychologists [14], [15], who studied the issues of self-organization and cohesion in small social groups, we will consider the following principles of behavior of robots in a team:

- The principle of independent achievement of the goal;

- The principle of the mutual utility of robots;
- The principle of "laziness" of the robot;
- The principle of "selfishness" of the robot.

Let's consider the named principles.

1) The principle of independent achievement of the goal. This principle assumes that robots, not knowing about the existence of other robots, their goals, and the possibilities of achieving the goal, try to achieve their own goal on their own.

All robots simultaneously apply their strategy r_i to achieve the target state g_i. Since the goals of robots can be different, aggregation of their strategies $\bigoplus_i r_i$ does not guarantee that each robot will achieve the goal. The equation for the dynamics of changes in the state of such a spontaneous team of robots has the following form:

$$Y^*(t+1)=W^\circ Y(t)\oplus(\bigoplus_i r_i).$$

For robots with close targets, i.e., $\forall R_i \in K$, $K \subseteq A$, $\rho(g_i, g_q) \leq \varepsilon$, $\forall R_i, R_q \in K$, ε is a criterion for the proximity of targets, achieving their goals is possible if their the aggregated strategy dominates the strategies of all other robots, i.e., if $\bigoplus_{R_i \in K} r_i > \bigoplus_{R_j \notin K} r_j$.

2) The principle of mutual utility. In [1], the principle of the utility of robots was formulated: robots R_i, R_q with similar goals are called mutually useful if the pooling of their resources increases the possibility of achieving a common goal g_Σ.

The implementation of this principle in work [4] involves the exchange of information between robots about their own goals, resources, and strategies for achieving the goal. If there is no information exchange, then to implement this principle we will use heuristic 1.

Heuristic 1. A robot with great goal-achieving capabilities is of great utility for teamwork. We will assume that, the closer the robot is to the target, the higher the probability of achieving the goal of the robot, i.e. to a foraging object whose parameters ($Y_q(t)$) need to be changed to target values (g_q).

Let us define the neighborhood of the robot's proximity to the target object ε_k, in which the robots are considered useful, i.e. $\rho(Y_i(t), Y_q(t))<\varepsilon_k$. Then a team of useful robots is formed by robots R_i for which $\forall R_i \in K$, $K \subseteq A$, $\rho(Y_i(t), Y_q(t))<\varepsilon_k$ are true, where $Y_i(t)$ are the parameters of the robot, $Y_q(t)$ are the parameters target object. The swarm dynamics equation is as follows:

$$Y_{iq}^*(n)=W^\circ Y(t) \bigoplus_{R_i \in K} r_i \bigoplus_{R_j \notin K} r_j.$$

The goal of a robots team K can be achieved if its aggregated resources are dominated by the resources of other robots.

3) The principle of "laziness" of the robot. In teamwork based on the principle of mutual utility (heuristic 1), in conditions where the resources of robots groups that are not part of the K team are unknown, pooling resources to achieve the goal of the robots of the team K may be redundant.

The principle of "laziness" of the robot allows you to combine the resources of robots in the amount necessary to achieve the goal. The principle of "laziness" of a robot is based on its control of the environment state at successive times. If the environment state $Y^*(t)$ changes in the direction of the robot's target R_i, then it is inactive, $r_i^*=0$. The lazy robot's heuristic is as follows.

Heuristic 2. The robot does not take any action if the state of the functioning environment changes towards its target.

Formally, the principle of "laziness" of a robot is expressed in the form of checking the condition $\rho(g_i, Y_i(t))>\rho(g_i, Y_i(t+1))$ by each robot, the execution of which leads to its inaction, $r_i^*=0$.

The process of forming such a "lazy" team is based on monitoring the state of the environment and does not imply the exchange of information between the team's robots.

In spontaneous teams of robots based on utility and "laziness", the best robots will do the work to achieve the goal, while the robots that have less ability to achieve the goal will be "idle". This disadvantage can be eliminated by adding to these principles the principle of "selfishness" of robots.

4) The principle of “selfishness” of a robot is based on the fact that robots receive a reward $O(r_i)$ for achieving a goal. All robots, regardless of their ability to achieve a goal, strive to achieve it and receive a reward. In teams based on the principles of utility and laziness, only the best robots will receive rewards. Those, $\rho(g, Y_i(t))>\rho(g, Y_j(t))\Rightarrow O(r_i)>O(r_j)$. The heuristic of the "selfish" robot is as follows.

Heuristic 3. Robots, which have not the best opportunities to achieve the goal, try to achieve it in the hope of getting a reward.

Formally, a team of selfish robots is formed by robots R_i for which $\forall R_i \in K$, $K \subseteq A$, $\rho(Y_i(t), Y_q(t))>\varepsilon_k$ are true, where $Y_i(t)$ are the parameters of the robot, $Y_q(t)$ are the parameters target object.

The principle of “selfishness” of robots (heuristic 3) allows you to connect robots that do not have great opportunities to achieve the goal into a team, thereby balancing the load of the entire team of robots.

The principles of operation of spontaneous robot commands assume that each robot has complete information about the state of the environment of functioning $Y(t)$. To fulfill its task of achieving the goal, the robot needs to know the current $Y(t)$ and target $Y^*(t)$ values of the target objects.

We will assume that uncertainty is possible both in the target values of the robot parameters and in the current states of the target objects. The rules of robot behavior under uncertainty are based on the generalization principle of an undefined parameter, which is that this parameter can take any value from a set of its possible values. The behavior of a robot based on the generalization principle is to search for an undefined parameter, objects that satisfy the search pattern [16].

In works [16], the principles of the functioning of spontaneous robots teams, based on the analysis by robots of the functioning environment state and not involving the information exchange by robots about their goals and resources, are considered. Variants of the robot's behavior in conditions of uncertainty in the parameters of the target object are considered. The analysis of the possibility of the formation of robots spontaneous teams in conditions of uncertainty is carried out.

3. Robots with qualitative BDI-architecture

Tasks that can be solved by a flock of reactive robots are specific tasks that do not involve the robot's actions outside of the actions laid down in the algorithms by the developer.

It is possible to expand the capabilities of groups of robots by using intelligent robots with cognitive capabilities close to those of humans. Intelligent robots have a mental BDI (Belief-Desire-Intention) architecture [5].

In the work [22], the architecture of a qualitative cognitive robot is proposed, which makes it possible to implement and study various principles of command behavior of intelligent robots with a BDI-architecture with less laboriousness while maintaining their basic properties.

Simplification of the cognitive architecture is achieved through the use of a qualitative ontology as a model for representing the agent's knowledge about the functioning environment, in the form of a conceptual framework of the functioning environment.

3.1. The architecture of a qualitative cognitive robot

The main elements of the intelligent agents’ architecture were defined in the InteRRap architecture proposed in [17]. It is a hierarchical knowledge base and an associated agent management component. Further, when building the architecture of a qualitative cognitive robot, we will focus on this architecture. Let us consider models of the main components of a quality robot: models of knowledge representation, behavior planning, cooperative interaction of robots.

3.2. Knowledge representation model of a qualitative robot

In the knowledge representation model of a qualitative cognitive robot, we will define quantitative and qualitative knowledge representation models.

In work [4], the dynamic system "group of robots-environment" is considered. Here, the robots functioning environment is determined by the direct product of sets of values of their properties, $SF=\underset{ij}{\times} Z_{ij}$, and the state of the robots functioning environment at time t is the vector of property values of all robots: $Z(t)=(z_{1e},...z_{1q},..., z_{ne},...z_{nq},)$.

The construction of a qualitative environment for the functioning of intelligent BDI robots is based on the interpretation of the state space SF as an attribute semantic space, in which the functioning environment states of $Z(t)$ (vectors of values of robots properties) are determined by the names and vectors of attributes values that determine their content (sense).

In this case, the states of the system "group of robots-environment" can be represented in symbolic form as signs-symbols. In the definition of the German logician G. Frege [18], the sign is a triple: the name, sense, and meaning of the sign. The name is a symbol denoting an object of the real world, the sense determines the properties of this object, and the meaning is the object itself. The use of sign models in control is given in [19], and models of sign pictures of the world, which can be used to describe the knowledge of agents - robots, are considered in [20].

In this work, in the state space of the dynamic system "group of robots-environment", in the semantic space, nested subspaces are distinguished that define the classes of possible states of the system [21]. These subspaces are structured in the form of a conceptual framework, in which all classes of possible states are named d^H and form a partially ordered set of subspaces $SS(d^H)$ of the state space of the dynamical system FS, i.e. $SS(d^H)\subseteq FS$.

Formally, a qualitative conceptual framework is defined as a partially ordered set of state class names:

$$KK^W=(\{d^H\}, \wedge ,\vee),$$

where $\{d^H\}$ is the set of names of classes of states d^H, which uniquely define the subspaces of the functioning environment $d^H\Leftrightarrow SS(d^H)$, $SS(d^H)\subseteq FS$, and the volume of the states' class $V(d^H)=R_i| R_i=(z_{1e},...z_{1q})\in SS(d^H)$.

3.3. BDI architecture of a qualitative cognitive robot

In [22], the elements of the robot BDI architecture are defined in terms of the KK^W conceptual framework.

The BDI robot's beliefs (knowledge) are defined by a tuple:

$$\langle BEL_i, W_i^{BEL}\rangle,$$

where BEL_i - beliefs of the *i-th* robot are represented as a partially ordered set of names of classes of states of the FS functioning environment, i.e. $BEL_i=(\{d^H\}, \leq)\}$, $d^H\Leftrightarrow SS_i(d^H)\subseteq KK^W$, $BEL_i \subseteq KK^W$;

W_i^{BEL} is the robot's knowledge about the laws of the functioning environment, which is represented by a mapping:

$$W_i^{BEL}: \underset{i}{\times} Z_{ji}\to \underset{i}{\times} Z_{ji},$$

where $\underset{i}{\times} Z_i$ are vectors of robot feature values, $\underset{i}{\times} Z_{ji}\in SS_{ji}(d^H)$, $d^H\in BEL_j$; W_i^{BEL} is a set of production rules (If, Then), reflecting the laws of the functioning environment.

The robots goals (Desire) are the vector $G=(z_{1i},...,z_{1h};...; z_{nk},...,z_{nr})$, $z_{ij}\in Z_i$, the elements of which determine the desired values of the properties of each robot in the functioning environment (FS) and are represented in terms of the names of the environment classes functioning:

$$DES_i=(d_1^{Gi}; d_2^{Gi}; \ldots; d_n^{Gi}),$$

where $d_j^{Gi} \Leftrightarrow SS_j(d^H) \subseteq KK^W$ are the names of classes of target states, $G_j \in SS_j(d^H)$ is the target vector of the *j-th* robot, $\forall j, j=1,\ldots,N$.

The robot's actions (Intention) in the functioning environment (FS) are presented in the form of a vectors set: $U_i(t)=(u_{i1}, \ldots, u_{in}) \in \underset{j}{\times} Z_{ij}^R$, and in terms of the conceptual framework are represented as a set of class names of states of the functioning environment:

$$INT_i=\{d_j^{Ui}\},$$

where d_j^{Ui} is the name of the action state class that defines its content $SS(d^{Uj})|\ U_i \in \underset{j}{\times} Z_{ij}^R \in SS(d^{Uj})$.

3.4. Quantitative and qualitative models of the functioning environment

Consider a homomorphic mapping of a quantitative model of the FS functioning environment into a qualitative symbolic model (conceptual framework), i.e. $\Psi: FS \rightarrow KK^W$. Here, any point of the environment $Z(t) \in FS$ is uniquely mapped to a state class named d^H, while the inverse mapping of the state class d^H is represented by the set of points of the subspace $SS(d^H) \subseteq FS$. The same mappings are valid for the beliefs $\langle BEL_i, W_i^{BEL} \rangle$, the goals of DES_i, and INT_i - the actions of the BDI architecture of robots.

The main idea of representing an intelligent robot in a qualitative functioning environment is that the description of this environment using the names of state classes allows us to propose simple logical conditions for the formation and functioning of a robot's team. Thus, in the architecture of an intelligent robot, within the framework of a qualitative model of a functioning environment, the tasks of team interaction of robots are solved, and the implementation of this interaction is carried out in terms of a quantitative model of the environment.

3.5. Planning the behavior of a qualitative robot

In the model of the functioning environment in the form of a qualitative conceptual framework, the solution to the problem of planning the robot's behavior can be represented as the solution of the inverse problem in the equations of the dynamics of this system.

The change in the state of the environment by the *i-th* robot, taking into account his knowledge of W_i^{BEL}, is represented by a system of logical-linguistic equations:

$$W_i^{BEL}:(Z^*(t), INT^*_i)) \rightarrow Z^*(t+1),\ \forall i,$$

where W_i^{BEL} is the knowledge of the *i-th* robot (the system of rules "If, Then"), $Z^*(t)$ is the initial vector of the state of the environment in terms of the names of the state classes, INT^*_I is the control (action of the robot), $Z^*(t+1)$ state of the environment after control in terms of names of state classes [22].

The search for actions to achieve a given goal vector by each robot is reduced to solving the inverse problem:

$$INT_i^* = DES_i \circeq W_j^{BEL}$$

where INT_i^* - actions of robots, allowing to achieve the goal DES_i, $\circeq$ - backward inference procedure [22].

INT_i^* actions are the set of $\{d_j^{Ui}\}$ state class names that the robot must transition to in order to achieve the DES_i goal.

3.6. Model of cooperative interaction of a qualitative robot

In the work (cross), the planning of the robot's cooperative behavior involves the construction of a general plan before starting to solve the problem of achieving a common goal. In this paper, we consider situational cooperation between robots, when a decision on joint actions is made by robots based on an analysis of the state of the functioning environment and the presence of conditions for cooperation in robots.

The criterion of the mutual utility of agents proposed in [4] is considered as a condition for the cooperation of robots. According to this criterion, a robot is selected as a partner, interaction with which is most useful for both robots.

The following conditions for the cooperation of robots have been formulated [22]:

1. Robot j is considered attractive for cooperation for robot i if the element of its goal $d_i^H \notin BEL_i$ exists in the belief system (knowledge) of robot j, i.e. $d_i^H \in BEL_j$.
2. Robot j is considered attractive for cooperation for robot i if there are elements $d_i^H \in BEL_i$ in its belief system, which are also elements of the belief system of robot j, i.e. $d_i^H \in BEL_j$.
3. Robot j can change the properties of robot i if the parameters of robot i belong to one of the possible classes of states of robot j, i.e. $R_i \in SS(d_j^H) | d_j^H \in BEL_j$.

Robots begin to exchange information about their resources and knowledge (beliefs), if one of them cannot achieve its own goal. For robots to work together, the above conditions are checked.

The first condition determines that the potential partner must have the opportunity (resources) to work together. The second condition determines that potential partners must have intersections of their conceptual systems (knowledge) beliefs. In this case, communication in terms of general knowledge is possible. The third condition is checked if the first two conditions are met. It is believed that the robot that asked for help must create the conditions for joint actions to be possible.

Thus, the robots' teamwork, in this case, consists of the exchange of information about their beliefs and goals in terms of the classes' names of states, and checking the conditions of mutual utility, and, therefore, the possibility of cooperation.

4. Conclusion

The paper considers models of command behavior of reactive robots and intelligent robots with qualitative BDI architecture. A mathematical model of the functioning environment of robots and a model of a formal robot are proposed. For reactive robots, the principles of the formation of spontaneous teams of robots based on the principles of social organization are determined. Heuristics of the behavior of robots based on the analysis of the state of the functioning environment, which do not imply the exchange of information about the goals and resources of robots, are proposed.

The architecture of an intelligent robot with qualitative BDI architecture is proposed. A feature of this architecture is the qualitative representation of the functioning environment in the form of a conceptual framework. A mathematical model of a qualitative intelligent robot with BDI architecture is proposed.

For intelligent robots, models of planning their behavior and conditions of cooperation are proposed. The proposed principles for the formation of reactive robots teams and the conditions for the cooperation of intelligent robots were investigated in the simulation of the mechanisms of formation and functioning of robot teams.

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