Multi-agent Robotic Systems in Collaborative Robotics

Sergey Vorotnikov(✉), Konstantin Ermishin, Anaid Nazarova, and Arkady Yuschenko

Robotic Center of Education and Research, Bauman Moscow State Technical University, Izmaylovskaya Sq., 7, 105007 Moscow, Russian Federation
vorotn@bmstu.ru

Abstract. This paper describes the principles of control of multi-agent robotic systems. It is a new area of robotics oriented for introduction of robotic not only into industry but into life of human. The main principles of collaborative robotics are the safety of human and easiness of robot control. The problem is how to control not a single robot but a group of robots working together. It is most important for such tasks as rescue operations, environment monitoring etc. Some approaches to solve the task of human control of a group of robots are presented in the paper.

Keywords: Collaborative control · Multi-agent system · Decentralized systems Dialog mode · Collaborative robots · Engineering education

1 Introduction

Collaborative robotics is a new stage in the development of the technogenic human environment. The basic requirements towards a collaborative robotic system (CRS) are the safety of the robot operating in a working area where a human being is also present, as well as the robot's easiness in handling, not requiring any special operator training. In our opinion, the term "collaborative robotics" is much broader than the frequently used "service robotics", because it is associated not only with the facilitation of human activities and the provision of certain services. CRS applied in various fields use groups of robots jointly solving common tasks. Two related problems arise here. The first is the need to provide for well-coordinated functioning of the individual robots that interact with each other and form the actual multi-agent robotic system (MARS). The second is the use of MARS in interaction with the person who manages the system, bearing in mind that the system agents might find themselves in an area where other people are also present. That said, management should remain simple enough for the operator, and the functioning of the robotic agents should be completely safe for the people and the technical equipment located in the MARS envelope area. We should point out that the application range of such systems is far beyond the examples mentioned above, as it is not limited solely to use in extreme environments. These can be health care systems in hospitals, involving the use of groups of robots for various purposes, and robots designed for training in schools and universities.

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It is apparent that the use of groups of robots puts forward new requirements both towards the structure of the navigation and control system, and towards the organization of interaction with the operator, as well as towards the very methods of controlling the individual robotic agents. In this case, we can refer to a new class of robotic systems, that is, the collaborative MARS.

2 The Structure of Multi-agent Collaborative RS

The "collaborativeness" concept significantly expands the opportunities of the group management of robots, both for manipulative and mobile robotics. As is known, the group management systems belong to the multi-agent systems type, and two basic approaches are used in their management: the centralized and the decentralized approach. The first is intended for cases where similar agents perform similar tasks. The second is effective if agents have diversified structures and are able to perform various tasks.

A collaborative mobile robot is an intellectual agent functioning in an environment that is not completely deterministic, and its task is not clear. An example of such a task is the patrolling of some large crowded space, say, airport, railway station, hypermarket, etc. The unified robotic system, including both fixed and mobile observation stations, has to identify potential offenders at transportation facilities.

The priority task is to design a hardware and software package that includes a computer vision system and a group of mobile robots, in order to detect, track and accompany people whose appearance and behavior is deviant, and to convey the information about such persons to the operator's post. It should be pointed out that the group has a common goal, according to the general task. The goal is further divided into local targets of individual robotic agents, with each agent having its own route. The agents' algorithms are not completely formalized, due to the fact that the actions of the surveillance object cannot be known in advance. For instance, the surveillance object can move into another robot's patrolling area, or another object may attract the agent's attention. The robot perceives the movements of people in its patrol zone as non-deterministic. Thus, the agents have to modify their preset algorithms, such as their routes, agreeing them among themselves and with the operator. Preliminary analysis has shown that the solution of complex problems under conditions of uncertainty primarily requires a distributed system of a hybrid type, combining the centralized and decentralized systems. Here, team management is performed by way of the agents' exchanging information. The managing center sets up tasks and deals with the processing of the current information.

Thus, a hybrid MARS unit includes a control center, a team of robotic agents with different "specialization" and auxiliary equipment. The human operator's functions include system monitoring and taking decisions in complex or difficult situations. The control center performs team management as a whole, giving appropriate commands, and processes the information received by the robots during the performance of their tasks. Depending on their functional abilities, the robots may perform surveillance, search or technological tasks. According to the tasks received from the control center, the robots exchange messages, join into groups and distribute tasks among themselves according to the specified optimality criteria.

The modular [1] structure of the MARS hierarchical control system includes four levels. The control center is the first level of the control system. It contains the instruction control unit which is responsible for the instruction sequence generation and for passing those instructions along to the robots; there is also a data processing unit which receives information from the robotic agents and from the auxiliary gauges and information tools. The second level is responsible for the overall planning of the MARS actions. It breaks down the tasks to be solved by MARS into simpler tasks and distributes them among the robots. Using the appropriate algorithms, target point coordinates for each robot are determined.

The third level provides the robots' movement trajectories via the local planning algorithms which are based on a method similar to the method of potentials. Generation of the motion trajectories requires knowledge of the robots' current coordinates in the workspace; this task is solved by the combined navigation system.

The fourth, executive, level performs the direct interaction between all MARS elements and the outer environment. It is responsible for the creation of control signals for the robots' drives, navigation sensors, special and auxiliary equipment, and it also supports the sensor system operation.

3 Scheduling

The implementation of both centralized and multi-agent (distributed) control methods requires solving of the global planning tasks. That is, a bigger task is to be broken down into smaller-scale tasks and distributed among the individual agents according to the general (global) task facing the group. In case of centralized management, the control center distributes the tasks among the team of robots according to the established optimality criteria. Usually, the task time serves as such criterion. The easiest way to solve tasks of **centralized control** is the direct search method. However, in most instances it is impractical because it takes too long. Evolution methods (genetic algorithms) also require considerable time due to their computational complexity. Due to this, a simpler weighted algorithm [1] has been worked out, tested and introduced. It allows managing a team of robots in real-time mode. The tasks to be solved by a group of agents are perceived as known. As it has been already said, all robots are similar and each task can be solved by several robots. For each robotic agent, the control center forms an array of weights $\{c_{ij}\}$, where $i = 1,2,\ldots,n$ stands for the robot number, and $j = 1,2,\ldots,m$ stands for the task number. This array contains the proposed tasks of a robot, for instance, the time or energy required to solve each task. The control center has to distribute tasks among the group of robots. so that to minimize the appropriate graphs of weights (Fig. 1a). For instance, for the first task a robot with the number "i" is selected and provided with $min_{i}c_{i1}$.

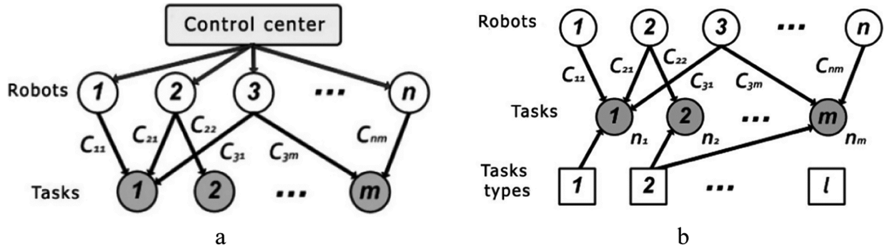

Fig. 1. Group task distribution patterns: centralized (a) and multi-agent (b).

When there are many robots in a group, centralized control appears to be somewhat inexpedient. Among its drawbacks, there will be low reliability of the system, heavy workload on communication channels and high consumption of computing resources of the control center. Besides, centralized approach will be ineffective for working areas with rapidly changing parameters.

The second pattern of task distribution among robots is devoid of these drawbacks. It is **multi-agent (distributed) control task** setting where agents themselves distribute their tasks to build the collaboration basis on the specified optimality criteria (Fig. 1b).

This task distribution is optimally achieved through "auction" type negotiation pattern which is based on information exchange between individual agents. At the auction, resources are announced which are required for the agents to achieve their goals; that is, they are, so to speak, "set up for sale". Resources are limited, and so the agents compete in the "bidding" process. When tasks are distributed among the robot team, tasks themselves serve as resources. The expediency of the "purchase", that is, assignment of specified tasks to each robot, is estimated by the set criterion of optimality [2]. On each stage of the auction, robot agents form their own weight arrays, and one of them becomes leader. From the responding agents, the leader chooses those who offer the lowest weight loss and sends them a command to carry out the task. At the next stage, another agent currently on standby will become leader. The auction is held until all tasks are distributed. Thus, multi-agent management pattern ensures self-organization of the system and increases its operational reliability. Comparison of the multi-agent patterns has shown that the task distribution algorithm based on the "auction" communication model, is much simpler from the computational point of view ($0.12 * n$ times, $n >> 8$) compared to another well-known multi-agent method of collective plan improvement [3].

For multi-agent task distribution, each robot agent has to be able to exchange information with all the other robots that make up the team. This problem can be solved by dividing of the team of robots into smaller groups, each having its leader agent who will be able to exchange data with the rest of the agent forming the group. The number of such leaders should be kept minimal. As a result, the robot team is broken down into smaller groups each having a leader. After that, within each formed group it will be possible to use the previously considered multi-agent task distribution algorithm.

The easiest task is uniform distribution of robots in the working area. A more meaningful task is to move robots to specified target points and to perform operations at these points. In the latter case, the control system has to provide robots with appropriate routes, that is, to solve local planning tasks. The appropriate algorithms are implemented on the third level of the control system (Fig. 2). They are basic for the trajectory formation unit. The kinematic analog of the well-known “method of potentials” can be used as the basic algorithm for trajectory formation. The implementation of this method ensures uniform distribution of robots in the work area when it is examined for emergencies. It also ensures the transfer of the robots to the required target points for the performance of technological operations. In both cases, this method enables the robots to avoid collisions with fixed and moving obstacles, including other robots. In particular, the considered method of multi-agent management was effectively used for mapping of terrain exposed to radioactive contamination [1]. The robots collecting data are evenly distributed across the work area and the required parameters are measured. The measurement results are fed into the control center database and plotted on the special-purpose local map.

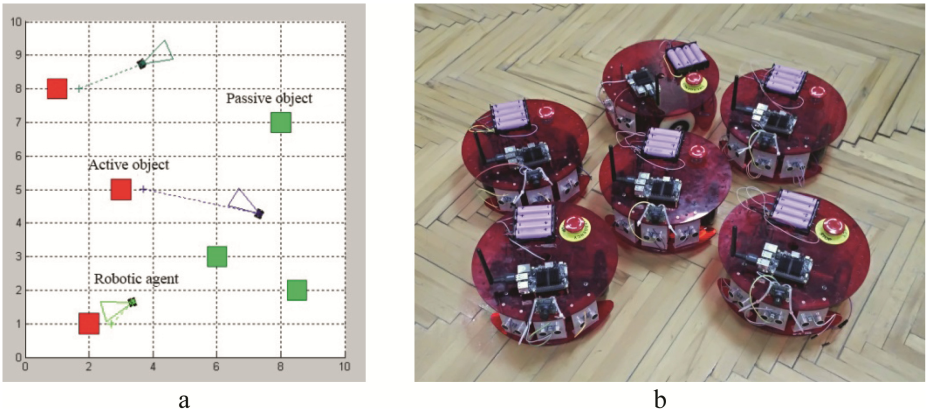

Fig. 2. Graphic model (a), mock-up specimen of robots (b).

4 Dialog Control of Multi-agent Robotic Systems

Management of autonomous mobile robots on the operator’s part takes form of setting the tasks and the dialogue accompanying the performance of those tasks. This management requires “natural”, from the human point of view, space-time relations [4] which greatly facilitate the task of controlling the robot. The description of a robot’s outer world includes both the description of objects relevant for the performance of the set task, and the spatial relations between the objects of the world, including the robot itself. Extensional and intentional fuzzy relations are used to describe the spatial relations between the objects of the working scene [4]. The first include the relationship of position and orientation of objects. For instance, “object $a1$ is far away, ahead and to the right of object $a2$”. Intentional relations include such relations as “to contact”; “to be inside”; “to be out”; “to be in the center”, etc. Using formal rules of conjunction and disjunction, from elementary spatial binary relations it is possible to obtain other relations encountered in practice.

The current situation embracing M objects, including a controlled robot, is described by a binary frame system (<object m>, <relationship>, <object n>), m, $n = 1,2,\ldots,M$. If the fuzzy binary relations between all objects that can be observed by the robot in the course of movement are set in advance, then we will get a fuzzy semantic network, or a fuzzy map. Using this map, it is possible, in particular, to navigate the robot along the observable benchmarks, i.e. the objects whose position was known in advance [5]. The image of the current situation may include other fuzzy features besides the spatial ones. [6].

Since the outer world is continuously changing both due to the movement of the objects under surveillance and due to the movement of the robot itself, the description of the situation will also vary with time. This circumstance requires taking into general consideration not only spatial but also temporary relations in the outside world, such as "to coincide", "to take place earlier", or "to follow". Such relations have to be used, in particular, for control of mobile robots moving around areas that contain other moving objects [7]. They make it possible to provide for automatic accompaniment of mobile objects, or to avoid collision with them.

Having described the current situation in the language of linguistic variables and fuzzy relations, one can specify the behavior of an autonomous robot in an external, not completely defined environment using fuzzy rules of the production type. These behavioral stereotypes have the form of production rules: "*if the situation is* S_i, *then the tactics is* T_i". Typical situations can be input in the robot's fuzzy knowledge base in advance, using the experience of the human operator. Using this database, a set of behavioral rules (tactics) can be drawn up that correspond to the pursuit of a new object, exit to a specific point shown on the electronic map, etc. The tactics themselves can be included into the robot's knowledge base by way of teaching a neural fuzzy system on which the fuzzy controller is based [8].

Operator can only inform the robot of the final goal of its movement in a space with a partially known structure. In this case, there arises the problem of autonomous traffic planning, which requires special consideration [9]. The planning is accompanied by a dialogue with the operator. The organization of the interactive control system involves the formation of a speech interface that includes a recognition module and a linguistic analyzer. The first module is a device for converting speech signals and interpreting them as separate words or phrases. The linguistic analyzer performs syntactic and semantic analysis of the statement, making it possible to fill-in the frame slots used for the description of actions [10].

5 Mobile Robotic Agent in Collaborative Robotic System

The control system of a mobile service robot is a two-tier architecture which consists of a base unit and an extension unit [11]. The base unit of a control system is responsible for controlling the movement of the mobile robot. It collects and analyzes sensory information, draws up a map of the working area, localizes the robot and its surrounding objects, schedules the route and manages the movements of the robot, including manipulation of objects.

The extension unit of the control system provides a mechanism for collaborative interaction of the robot with the human companion in the natural language. They interact through a dialogue block, with the help of which the human companion forms a sequence of tasks for the robot. When a task is formed in a natural language, its description is related to the working area topography, geometric coordinates indcated on the room plan, or is linked to certain objects or interaction with them.

Multimodal representation of the surrounding space in the form of a multi-layered map of the robot's working area provides for the mobile service robot's safe movement and effective interaction with its human companion.

A robot designed by Applied Robotics Ltd can be considered as an example of a mobile collaborative robot. It is a multifunctional robotic complex intended for various service and educational tasks. It consists of a differential type mobile chassis, anthropomorphic torso with two movable manipulator hands having five grades of mobility, and a head with two grades of mobility. The height of the robot is 130 cm. The load-carrying capacity of the manipulator arm is 0.75 kg, the battery life is 8 h.

The control system of the mobile collaborative robot is based on a combined modular hardware and software complex. The hardware complex includes navigational, onboard and multimedia controllers. Navigational controller processes the sensory device readings, builds a map of the surrounding space, detects the position of the robot and the objects around it, arranges the robot's routes and controls its movement. The onboard controller is the key element of the robot's control system. It is intended for the implementation of the basic robot control programs and for the management of functioning of the robot's systems. The multimedia controller is intended for the implementation of the of the robot's human-machine interfaces, such as remote telepresence system, speech dialogue system and graphic information visualization system. The robot functions in cooperation with a human companion, who manages the robot through natural language speech commands.

Besides interaction with the human companion, the robot can interact with people around it, when it encounters them on its route. In this case, the robot has to plan its further route so that to ensure traffic safety. Since the robot is operated under restricted conditions, i.e. among people who are constantly near and who move in close proximity, the robot control system is designed so that it would be able to assess the environment it is interacting with.

The robot's onboard sensor systems represent the surrounding space as an aggregate of a topographic plan, security areas, traffic control areas and a local map. The topographic plan is a geometric plan of the room divided into zones which are further subdivided into traffic control zones and zones associated with the job performance. The surrounding environment is clarified by way of compiling the information from a variety of different local maps obtained from the onboard sensor systems. For instance, the map received from the laser-beam scanning range meter will be used for the robot's localization on a topographic plan, and the map taken from the array of sonars located around the robot's perimeter will show the presence of objects around the robot during its movement. As a result, the assessment of the working area alteration, together with the task posed, allows to form a sequence of safe robot maneuvers for movement in rapidly changing constrained conditions.

6 Educational Complex for Studying the Methods of the Collaborative Robotic System Management

To test the various group behavior scenarios of robotic agents and to prevent possible collisions, the Center for Education and Research "Robotics" of the Bauman Moscow State Technical University has designed a software model for decentralized control of a group of mobile wheeled robots in the Matlab[1] environment (Fig. 2a) and their large-scale models (Fig. 2b).

The simulation was performed to solve the tasks of planning the robotic agent's actions in the group and the actions of the group as a whole. The simulation also provided for a possibility of obstacles (passive objects) hindering the movement of an individual robot along its route, which the robot had to bypass in automatic mode. When were present in the working area, one of the tasks of the robotic agents was to select the tracking object automatically taking into account the distance and the orientation of the appropriate robotic agent. At the same time, it was possible to automatically engage another robotic agent in tracking of the object. In turn, it required redistribution of escort objects among the robotic agents.

The studies have shown that the centralized group planning system is too complex from the computational point of view, because it depends on the number of agents in the group. Besides, it significantly complicates information exchange between the robots and the operator. Therefore, for the model development we used a method that we called "method of distributed action planning". In this case, each robot of the group independently solves the task of planning its actions in the current situation. A robotic agent which is a member of the group can change its actions solely on the basis of information concerning the current state of the environment, current situation and actions of other robots of the group, for a certain time interval. A desired action of a robot in the current situation is an action that contributes the most towards the achievement of the common (group) goal, i.e. gives the maximum possible increment of the target functional.

The modeling assumed that the "effect" of R_j robot achieving the goal $X_i \in \{X\}$ was determined by the meaning of a certain a priori efficiency assessment $d_{ji} = F(S_j, X_i, K_i)$, where K_i is the priority of the target X_i. Then, the task of target allocation within the group of robots will boil down to the need to distribute robots R_j $(j = \overline{1, n})$ among the subjects X_i $(i = \overline{1, m})$ so that to obtain the maximal cumulative effect

$$Y = \sum_{j=1}^{n} d_{ji_j},$$

where i_j is the number of target X_i selected by robot R_j.

The formation of the functional took into account that the number of the robots in the group n_i sent to the same target X_i at the same time should not exceed a certain $n_i^{\max}$, $i = 1,2,\ldots m$, which is selected based on the required group behavior strategy, and

[1] The mathematical and software models were developed by V.G. Ponomaryov.

depends on the target priority, or on the correlation between the number of the robots and the targets.

Agent's control system includes two levels. The upper level (the action planning module) is intended for constructing of the robot's route and for setting the task to the lower level (the route module) that forms the control of the robot drives.

The action planning module of a robotic agent implements an iterative procedure for optimizing the collective solution in accordance with a given efficiency criterion, say, minimization of the total distance covered by the robots. The central part of this module's pattern is PU processor node PU, implemented as a finite automaton. The PU input unit receives information about the ID of the object, vector E denoting the environmental situation, vector S denoting the robot's condition, vector K denoting coefficient, and S_M vector denoting the route module condition. At the output, the elements of the action vector A = (T, S) and the vector of the robot condition CS are formed.

For full-scale testing of the decentralized collective management model, prototype robot mock-ups were made featuring a traditional three-wheel scheme with two driving wheels and a two-level control system. The upper layer is implemented on the basis of Odroid controller with installed ROS (robot operating system) and ultrasonic range-finders. It is intended for dealing with the navigation issues (routing, obstacle avoidance, etc.), escorting of objects and communication with the operator and other robots through Wi-Fi. The lower layer implements the route module and uses the Arduino UNO processor which performs the function of the drive controller with PI regulator of the speed of the driving wheels.

A functioning action planning module was subjected to analysis, within the framework of the robotic system modeling. It required two series of ten experiments where robots and targets were placed randomly in the working area. The findings showed that the iterative procedure of the group decision optimization allowed to distribute robots according to their goals in a short time. By the third step of the iteration, more than 60% of the robots have made the final selection of the target.

The developed complex makes it possible to conduct comparative studies of various methods of managing a group of robots under the control of a human operator. Its use has shown its effectiveness as a tool for researching and developing new methods for collective robot management in collaborative robotic systems.

7 Conclusion

The development of robotics enters a new phase, when remote control of mobile and manipulative robotic devices gives way to collaborative control where the robot becomes an equal partner of the human operator, fully participating in the task solving process. The operator's task is substantially simplified, and specialized training is no longer needed. However, the robotic system in itself becomes more complex; now it possesses a high degree of autonomy and has capabilities that are usually referred to as artificial intelligence. Today, the problems are posed, primarily, by the capabilities of computer technology which has to assess the current situation and to manage mobile robots in real-time mode, taking into account sufficiently high speeds of movement.

Another source of the problem is the psycho-physiological capabilities of the human operator who manages autonomous activities of mobile robots in the outside world.

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