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Application of Distributed Robotic Systems in Earthquakes: Search, Planning and Control Abstract

In order to search and rescue injured during earthquake, we proposed a method for multi-robots motion planning and distributed control in this paper. At first, we have created two probabilistic search models to considering the search area and the characteristics of sensors, which we used to search the injured targets. And after finding the targets, they are assigned to the mobile robots on the land to afford emergency rescue. In order to reach to the targets, a path planning method based on map matching is proposed. There are three parts here. Firstly, to obtain the global and local map: continuous ground images are first collected using the UAV's vision system, and subsequently, a global map of the ground environment is created by processing the collected images. The local map of the ground environment is obtained using the 2D laser radar sensor of the leader (UGA). Established the coordinate conversion relationship between UAV and UGV, unknown values during map matching are determined via the least square method. Secondly, our robots moved by group (leader-follower). The leader's path was planned globally and locally. The other multi-robots moved along the path planned by the leader. Thirdly, in order to plan and coordinate the robots in the group, the finite state machine is used to describe the logical level of control system for each robot in the group. After that, at the tactical level of the control system, the movement control law of formation maintaining mode and formation switching mode is designed.

Keywords: *multi-robot, target search, probability theory, path planning, map matching, logical control level, tactical control level*

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Применение распределенных робототехнических систем при землетрясениях: поиск, планирование и управление

Обсуждаются новые методы планирования движения и управления группой роботов, способных к автономному поведению при землетрясениях. Процесс поиска включает наблюдение беспилотного летательного аппарата (БПЛА) за пострадавшей зоной и постановку текущих задач планирования движения наземных роботов. Для этого разработан способ поиска пострадавших с использованием аппарата теории вероятности. С учетом характеристик поисковой зоны и используемых датчиков созданы две вероятностные модели. После поиска цели предложен и исследован алгоритм построения программной траектории ведущего наземного робота на основе сопоставления карт. Разработана методика процедуры формирования глобальной карты с использованием изображений от камеры БПЛА и сформирована модель сопоставления карт в системе координат робота, которая обеспечивает получение требуемых параметров матрицы перехода в процессе сопоставления глобальной и локальной карт. Проведено глобальное и локальное планирование траектории движения ведущего робота. Разработаны логический и тактический уровни системы управления группой роботов, обеспечивающие управление перестроением и движением группы с сохранением конфигурации. Представлен способ решения задач логического управления группой беспилотных наземных аппаратов (БПНА) с использованием аппарата конечных автоматов. Отмечена необходимость использования логического уровня системы управления (СУ) группой БПНА для обеспечения смены конфигурации группы при движении. Разработан механизм планирования и координации поведения роботов в группе. В качестве компонентов логического уровня СУ каждым роботом в группе использованы конечные автоматы. Предложена эффективная стратегия предотвращения столкновений роботов при изменении топологии группы и одновременной смене положений роботов. На тактическом уровне СУ решена задача формирования закона управления движением группы наземных роботов в двух режимах: перестроения и движения с сохранением конфигурации. Приведены результаты компьютерного моделирования в среде ros_stage.

Ключевые слова: *группа роботов, поиск цели, теория вероятности, планирование траектории, сопоставление карт, логический уровень управления, тактический уровень управления*

Introduction

Because of the rapid development of intelligent manufacturing technology, communication sensors and artificial intelligence, the working environment of robots has expanded from a structured and certain manufacturing environment to an unknown and dynamic natural environment. The control of robots has also changed from single point control to distributed and scalable cluster control. As one of challenges facing by the academician, E. P. Popov's robot college in Moscow State Bowman University of technology, the professor S. L. Zenkevich has been focusing on researches on robot technology since 1990. His doctoral thesis is "The control, simulation and software of complex robot technology system" [2], which mainly concentrates on the structured manufacturing environment and makes use of the distributed robot system to do theoretical research on control, simulation and programming. This is a prelude that S. L. Zenkevich and his team started to study all aspects of distributed robots. It brings further theoretical research on the technology of organizing and controlling distributed mobile robots, which improves the autonomy and intelligence of robots in unknown, dynamic and complex conditions in different environments. The achievements of the theoretical research of the professor S. L. Zenkevich's team in this field in the past 10 years have facilitated the operation of combined robot technology tasks. In the distributed robot technology system, the sensor information of every robot can operate well with each other to make the system as a whole system to get higher data redundancy and better reliability. Several robots can work at the same time and provide solutions for many complex tasks with their interaction when doing complex tasks, which can not be operated by one robot itself. For example, distributed robot system can be used to search for victims and convey necessary supplies to the disaster areas in earthquakes. In operations of search and rescue, a series of tasks need to be solved (Fig. 1), which integrates target search [5, 6], movement planning [7] and the control of a single robot and the entire system [8]. They include a victim search algorithm based on probability theory, a scheduling algorithm for robot trajectory planning based on a matching map which use UAV and main ground robot data and a reconfiguration control strategy for a ground robot team in an obstacle environment.

Using probability theory instrument to study the search process

We use probability theory to solve the target problem of searching for rescuers in earthquakes. There are many types of sensors used to detect survivors, which are acoustic, radar and so on. Each sensor has its own characteristics and advantages, but radar sensor and infrared sensor are more suitable for earthquake due to their detection distance to the target. In view of the characteristics of these sensors, we established a detection model and studied the victim search process of a single robot in discrete and continuous cases the victim search process of a single robot in discrete and continuous situation. Therefore, a series of joint search problems can be solved.

In order to achieve these goals, we build the topographic map and the probability model of the sensor firstly [9].

1. Topographic map model. Assuming that there is a $L_x \times L_y$ topographic map, including a priori information $\rho(x, y)$ about the probability density distribution of the target, the total probability of finding the target on the map is $\iint \rho(x, y) dxdy \leqslant 1$.

If we use a grid of size $M \times N$ to quantify the continuous map, the probability of finding the target on the grid map is

$$\sum_{m=1}^{M} \sum_{n=1}^{N} c(m,n) \leqslant 1.$$

2. Sensor model. The conditional probability of target detection is very important in the case of grouped observations. If the target is in the visible area of the sensor in one observation, it will be recorded

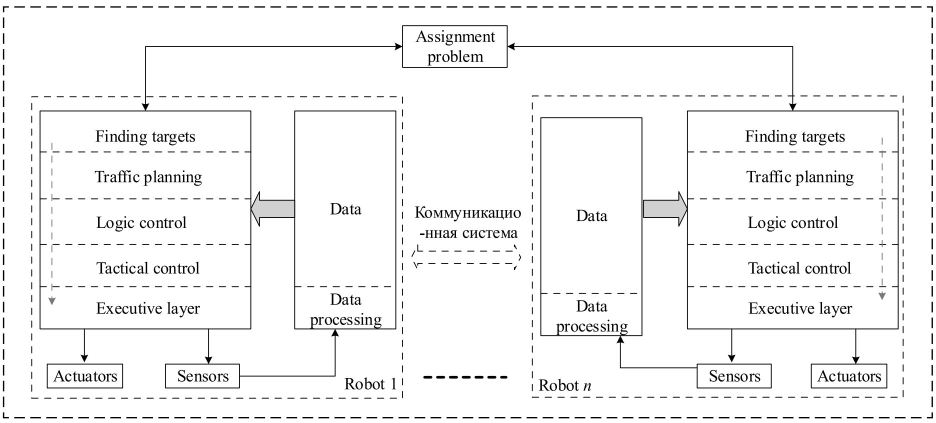

Fig. 1. The structure of tasks solved in a distributed robotic system

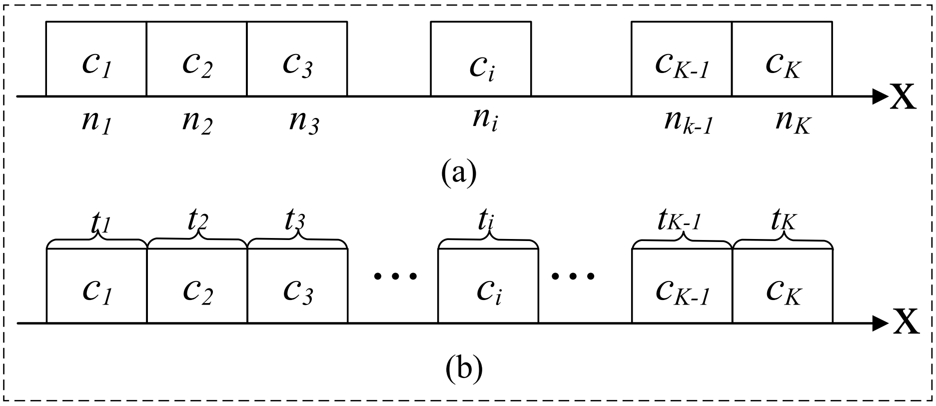

Fig. 2. Target detection models in discrete (a) and continuous (b) situations

as s and depended on the characteristics of the sensor and the average distance between the sensor and the target. When the observation is continuously searched, each observation requires a little time Δt. The conditional probability of detecting a target in a unit is $s = \alpha\Delta t$ and α depends on the characteristics of the sensor and the average distance between the sensor and the target. In continuous search situation, the probability of detecting a target is a continuously decreasing function, which is the distance between a specific sensor and the target $s = \alpha(z_k|l_k)\Delta t = \lambda(l_k)$ (Fig. 2). Discrete search has a similar function and the observation value $z_k \in$ {1, 0} and the number 1 indicate that the target is detected and the number 0 indicates that the target is not detected. l_k indicates the distance between the sensor and the target. $P_D \in [0, 1]$ indicates the probability that the sensor detects the target (taking the uncertainty of the observation into account t). $P_F \in [0, 1]$ is the probability that the sensor sends out a false alarm. l_{in} is the maximum distance that the sensor can observe the target with a probability. l_{in} is the minimum distance that the sensor cannot detect the target. But if the probability of its existence is P_F, it means that the sensor sends out a "false alarm". Then,

$$\alpha(z_k|l_k)\Delta t = \begin{cases} P_D & (l_k \leqslant l_{in}); \\ P_D - \dfrac{(P_D - P_F)(l_k - l_{in})}{l_{out} - l_{in}} & (l_{in} < l_k < l_{out}); \\ P_F & (l_k \geqslant l_{out}). \end{cases} \quad (1)$$

If T is the search time, P_T is the probability of detecting the target within the time and then you must understand P_T when analyzing the parameters and the search procedure.

Now let us analyze the situation of Ksensor observation units (Fig. 2). The target may be contained in one of the units. In the discrete search, each cell is observed n_i times. In continuous search, we observed i unit during t_i time, then

$$\begin{cases} P_K^n = \sum_{i=1}^{K} c_i(1-(1-s)^{n_i}); \\ P_K^T = \sum_{i=1}^{K} c_i(1-e^{-\alpha t_i}), \end{cases} \quad (2)$$

If several detectors explore the plane, then a joint search target strategy must be formed.

(a) Let one detector observe $2K$ units and the observation time of each unit is t_i^A (Fig. 3, *a*). Then, the probability of detecting the target in at least one cell in $T_1 = \sum_{i=1}^{2K} t_i^A$ time is

$$P_{2K}^{T_1} = \sum_{i=1}^{2K} c_i(1-e^{-\alpha t_i^A}).$$

(b) If two detectors observe $2K$ units at the same time and each detector observes its own unit at t_i^B time and τ_j^B (Fig. 3, *b*), the probability of detecting a target in at least one cell at $T_2 = \sum_{i=1}^{K} t_i^B$ time and $T_2 = \sum_{j=K+1}^{2K} \tau_j^B$ is

$$(P_{2K}^{T_2})^B = 1 - \left(\sum_{i=1}^{2K} c_i e^{-\alpha t_i^B} + \sum_{j=K+1}^{2K} c_j e^{-\alpha \tau_j^B}\right).$$

(c) Let two detectors observe $2K$ units at different time. The first detector observes each unit at t_i^C time and after $T/2$, the second detector starts observes each unit at τ_j^C time as shown in Fig. 3, *c*. Then, the probability that the target is detected in at least one cell within $T_3 = 2\sum_{i=1}^{2K} t_i^C$ and $T_3 = 2\sum_{i=1}^{2K} t_i^C$ is

$$(P_{2K}^{T_3})^C = 1 - \sum_{i=1}^{2K} c_i e^{-\alpha(t_i^C + \tau_i^C)}.$$

(d) If two detectors examine $2K$ units at the same time and each detector examines its *own* unit in t_i^D time and τ_j^D (Fig. 3, *d*), the probability of detecting a target in at least one cell in $T_4 = \sum_{i=1}^{2K} t_i^D$ and $T_4 = \sum_{j=1}^{2K} \tau_j^D$ is

$$(P_{2K}^{T_4})^D = 1 - \sum_{i=1}^{2K} c_i e^{-\alpha(t_i^D + \tau_i^D)}.$$

If the probability c_i is symmetrically distributed, which is $c_K = c_K + 1$ $c_{K-1} = c_K + 2$ ..., the com-

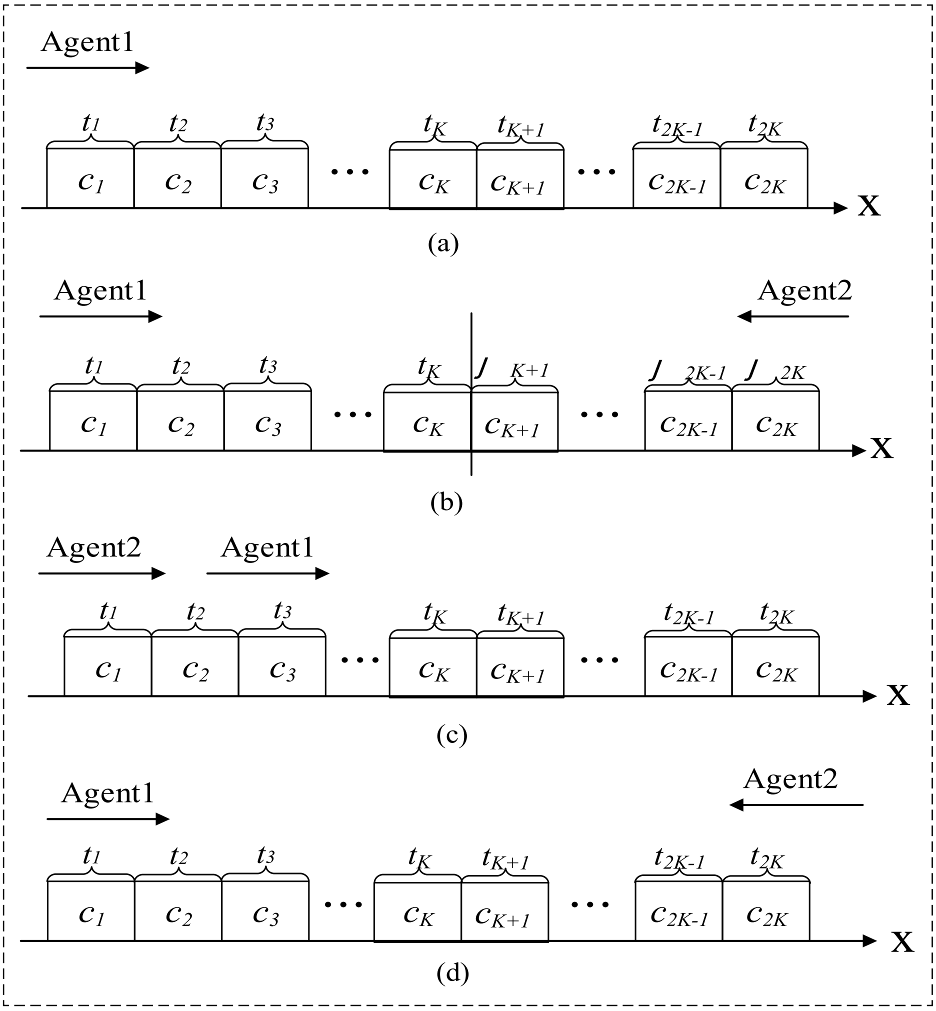

Fig. 3. Target detection strategies

lem so that other robots can deliver the required goods to the target. Obviously, the environment will change dramatically due to the earthquake so the existing map (Yandex map or Google map) becomes unimportant. Therefore, UAVs are suitable for the tasks of drawing global maps and global movement trajectory planning of robot groups because they provide a wide field of view and flexible maneuverability. Damaged buildings may collapse again due to repeated impacts (car impacts) and real obstacles that are not on the global map drawn on the basis of a series of drone images may appear. In order to solve this problem quickly, a leading robot on the ground team equipped with a camera, laser rangefinder and GPS must draw the local map. Accordingly, global and local maps must be compared to clarify the current situation. Fig. 4 shows the program trajectory drawing algorithm based on map matching.

In order to generate a global map, a series of operations must

parison of the four methods shows that: (a) $(P_{2K}^T)^a - (P_{2K}^T)^b \leqslant 0$. (b) because in the second situation, the search time is twice, which is $2(P_{2K}^T)^a - (P_{2K}^T)^b \geqslant 0$. (c) if the search time is doubled, the probability of target detection is halved $(P_{2K}^T)^a - (P_{2K}^T)^c = 0$ and $(P_{2K}^T)^b - (P_{2K}^T)^d = 0$. If the search parameters are unchanged, different search methods will lead to the same result. Under the same search time, there is no difference in the probability of target detection.

Therefore, when we perform the tasks, if the search parameters does not change, different search methods (with or without duplication) will lead to the same results. According to the number of existing drones, the search area is divided into Separate area.

Path planning of a group UGV based on map matching

When finding a target during the time of searching robots, we need to solve the trajectory planning problem so that other robots can deliver the required goods to the target.

be performed [10]: image registration, image splicing, object detection, and finally a global map. The main robot uses the SLAM method [11] to draw a local map based on the data of the laser rangefinder. Harris algorithm obtains a set of feature points (A') on the global map and compares them with similar points (A) on the local map. The relevance (c_θ) of the straight line segment connecting the feature points on the local map and the boundary of the obstacle on the global map can be recorded as:

$$c_\theta = \frac{{}^L c_k \, {}^L c_{k+1} \cdot {}^R c_n \, {}^R c_{n+1}}{\left|{}^L c_k \, {}^L c_{k+1}\right| \times \left|{}^R c_n \, {}^R c_{n+1}\right|}, \quad {}^L c_k \in A', \; {}^R c_n \in A. \qquad (3)$$

In order to analyze the relevance of the data, a critical value c'_θ is defined. If $c_\theta < c'_\theta$, the line segment is not related to the edge of the obstacle, otherwise a corresponding pair of points will be generated Q and Q' (where $Q \in {}^L c_k$ and $Q' \in {}^R c_n$).

After getting the global graph and the local graph, it is necessary to start to solve their com-

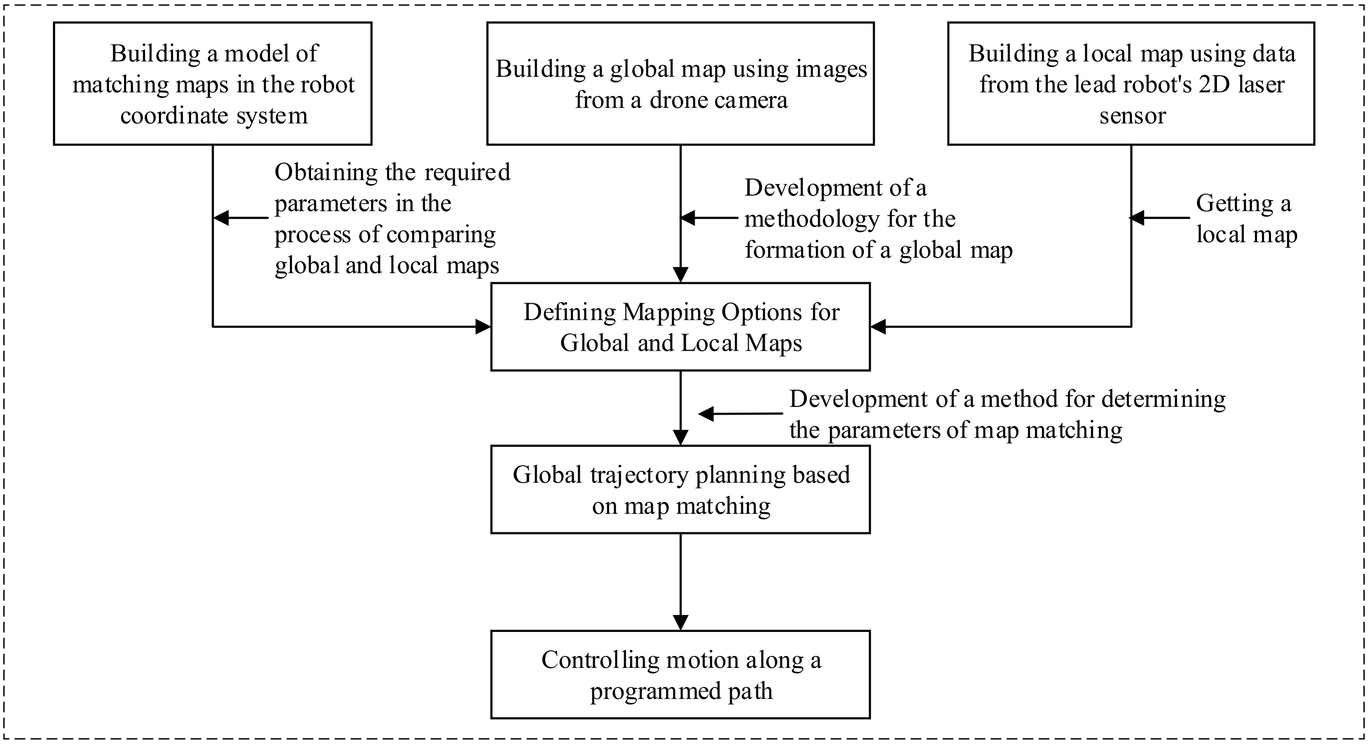

Fig. 4. Algorithm for constructing the trajectory of the leading robot

parison task. Supposing that it is a fixed point belonging to the terrain (Fig. 5) and its vector r_o is in the absolute coordinate system (CS). On the other hand, r_g is a vector defining the position M of the point in the drone coordinate system, obtained by its camera. Then, by transforming the coordinates

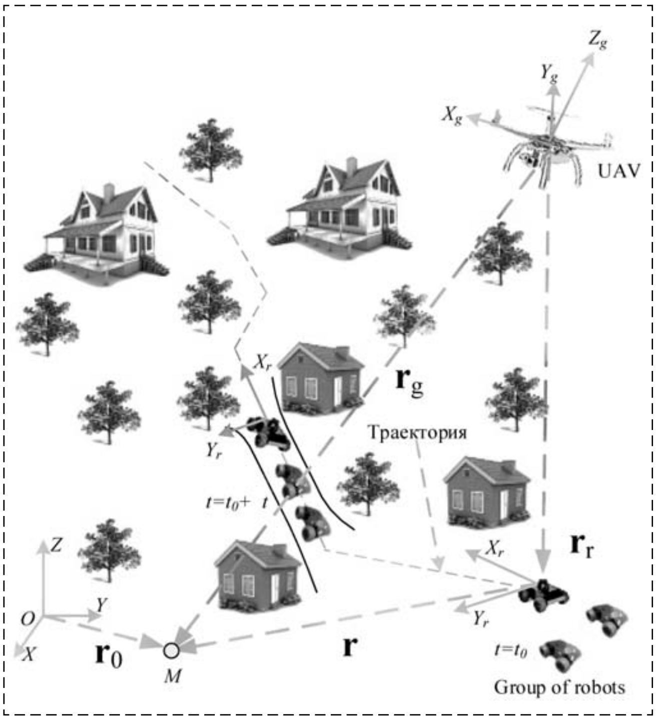

Fig. 5. Coordinate systems of the UAV and the leading robot of the ground group

from the drone coordinate system to the CS of the main ground robot, we get $r_r = T_r^{-1} T_g r_g$, where is the transition matrix from the coordinate system related to the drone and the main robot to the absolute CS. The position vector of the determined point T_g, T_r in the leading robot CS can be obtained using the scanning laser rangefinder to measure the endpoint coordinates to obtain.

Then the relation for comparing the global and local maps has the form [12]:

$$\mathbf{r_r} = \mathbf{Tr} = \begin{bmatrix} \cos\theta & -\sin\theta & x \\ \sin\theta & \cos\theta & y \\ 0 & 0 & m \end{bmatrix} \mathbf{r}, \qquad (4)$$

where θ, x, y, m is the rotation angle, translation coordinates and scale between the vectors $\mathbf{r_r}$ and $\mathbf{r}$, respectively.

Use the error squared minimization method $\varepsilon = \min \|\mathbf{T}\mathbf{r}_i - \mathbf{r}_{\mathbf{r}i}\|^2$, $\mathbf{r}_{ri} \in Q$ and $\mathbf{r}_i \in Q'$. It's not difficult to find these singularity pairs of matrices $\mathbf{T}$:

$$\begin{cases} \mathbf{T} = \mathbf{r}_{\mathbf{r}i}\mathbf{r}_i^{-1}; & \text{if } i = 4 \\ \mathbf{T} = (\mathbf{r}_i^T \mathbf{r}_i)^{-1} \mathbf{r}_i \mathbf{r}_{\mathbf{r}i}; & i > 4 \end{cases} \qquad (5)$$

Once the relationship of the objects in the map is established, we can proceed to solve the problem of global and local motion planning. According to the UAV map, the global planning generates a sequence of movement points of the mobile robot from the initial position to the target position, using an improved A* algorithm that takes into account the movement constraints. After obtaining the global trajectory, using the data from the scanner, the dynamic window method is used to locally plan the movement of the main robot along the global trajectory.

Reconfiguration control strategy of robot group in an environment with obstacles

In a constantly changing external environment, or when adjusting tasks assigned to a robot group, it is difficult to maintain a specific formation when the group of robots perform required actions. Therefore, in order to move the robot group quickly or avoid obstacles, the strategy of controlling the rearrangement of the machine group should be formulated at the logic level of the control system, and the method of controlling the movement of the robot group should be formulated at the tactical level [13].

The logical level of the robot group control system. The logic layer is responsible for changing the motion parameters of the robot group in an environment with obstacles, and coordinating their actions according to the results of the tasks performed by the corresponding robots. The robot group behavior realizes the following modes [14]: formation or dissolution of formations, movement of formations, robots joining formations, robots leaving formations, separation of formations and unification of formations.

The author developed a control method using the device of the terminal automatic device theory. This article uses a functional terminal automatic device and its description includes an additional function that is executed in each state. Fig. 6 shows the structure diagram of the logic level of the robot group control. The function of the group coordinator is to control the behavior of individual robots in the formation according to the operator's command, and to coordinate their actions according to the results of the manipulation performed by the respective robots. The coordinate azimuth instrument of the escort aircraft is recorded by a multi-import terminal automatic device (Mealy machine, Fig. 7, *a*). Its input is the value of a logical expression, and the output is a logical command to the corresponding robot.

Automata A_i are used to describe the logical model of individual robots, which is a Moore automaton (Fig. 7, *b*). Thus, the control system for an individual robot becomes two-level: the lower level

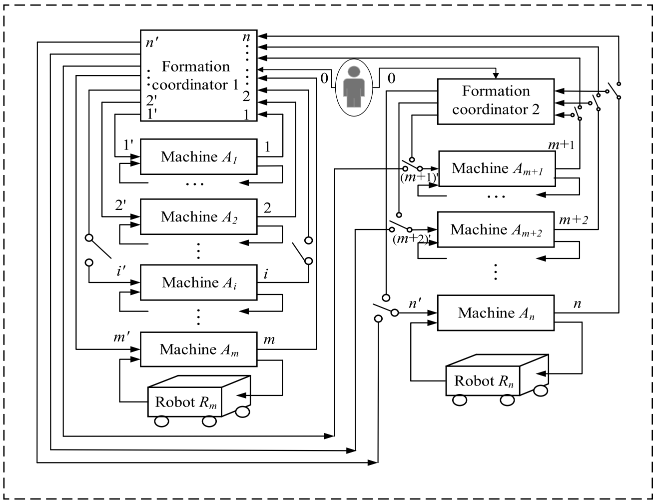

Fig. 6. Block diagram of logical control group robot

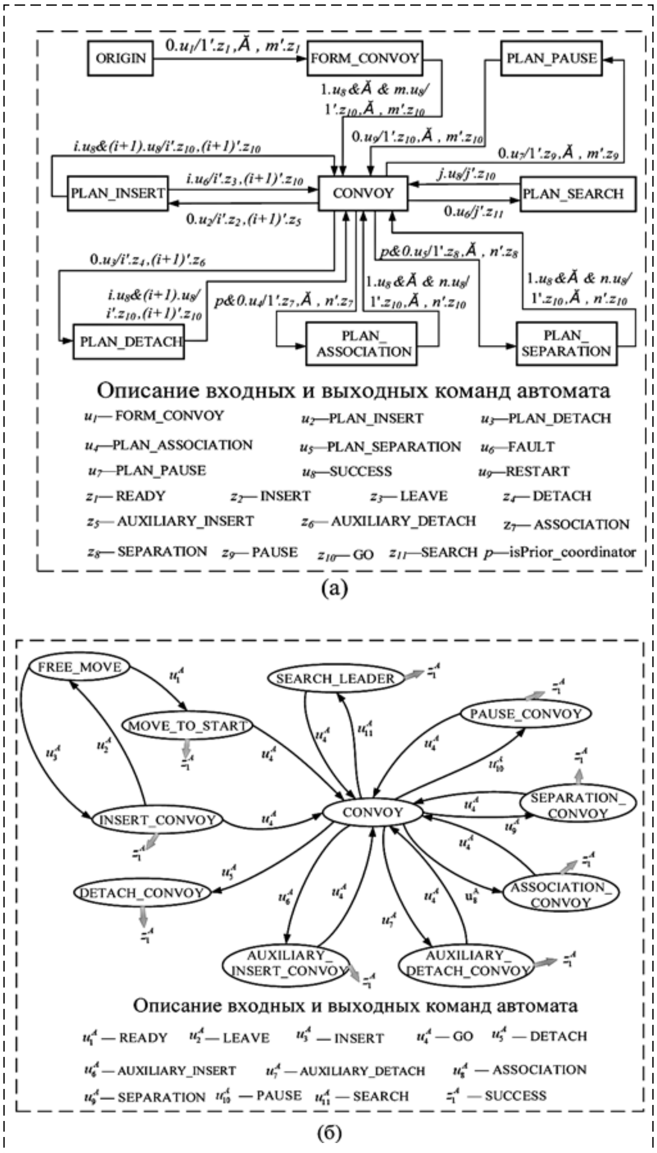

Fig. 7. Convoy coordinator as a control automaton (a); Logical model of a separate robot (b)

provides direct control of the actuator by virtue of the selected control law, and the upper (logical) one chooses one of these laws depending on the team of the group coordinator.

When the topology of the robot structure changes, it is necessary to ensure that collisions are prevented when it is rearranged. The corresponding algorithm is formulated according to the following steps [15]:

Step 1: Set the target position of each robot $F_g = \{\mathbf{r}_i'\}$, the safety distance between d robots, the speed module v, the critical value of the target distance d^* and the control command.

Step 2: Obtain the current coordinates of each robot $F_g = \{\mathbf{r}_i\}$, calculate the distance from the current position $d_{ig}(t)$ to the target position $d_{ig}^2(t) = (\mathbf{r}_i - \mathbf{r}')^T(\mathbf{r}_i - \mathbf{r}')$, and obtain the distance between the robot R_i and R_j $d_{ij}^2(t) = \mathbf{r}_{ij}^T\mathbf{r}_{ij}$, $\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j$.

Step 3: If $d_{ig}(t) \leqslant d^*$, that is, the robot has reached the target position, switch to step 6, otherwise, go to step 4.

Step 4: if $d_{ij}(t) > d$, the robot can move along its trajectory within time t, then go to step 3. If $d_{ij}(t) \leqslant d$, there is a possibility of collision between the robot and the robot goes to step 5.

Step 5: If $d_{ig}(t) > d_{jg}(t)$, the robot stops and skip, otherwise the robot stops. Then it goes to step 4.

Step 6: The algorithm ends.

The tactical level of the motion control system of the robot group. The essence of the tactical level is to develop a method to control the movement of the robot group in two modes: a reconstruction mode and a movement mode that saves the configuration.

When the topology changes, all robots know the initial and target positions of other robots so they know their planning trajectories and collision avoidance strategies. The reconstruction control method of each robot includes the method of relative distance and direction, which can be recorded as:

$$\begin{cases} v_i = k_{vi} l_i; \\ \omega_i = k_{\omega i}(\alpha_i - \theta_i), \end{cases} \quad (6)$$

where $l_i = \|\mathbf{r}_i - \mathbf{r}_i'\|^2$, $\alpha_i = \mathrm{arctg}(\mathbf{r}_i, \mathbf{r}_i')$, $\mathbf{r}_i$, θ_i — the position and direction of the robot at the current time, $k_{\omega i}$ — parameter.

On the other hand, after the rearrangement, the robot group must follow the basic control law-move while maintaining a certain configuration. The control method is based on the three rules of the decentralized control algorithm proposed in [16]. Using these rules (separation, alignment, and formation), the control signal is calculated as follows:

$$\begin{cases} \mathbf{v}_i = k_v \mathbf{V}_i + k_c \sum\limits_{|\mathbf{r}_{ij}|<d} \left\{ \dfrac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|}(d - |\mathbf{r}_{ij}|) \right\} + k_\varepsilon \varepsilon_{pi}; \\ \omega_i = k_\omega \varepsilon_{\varphi i}, \end{cases} \quad (7)$$

where $\mathbf{v}_i = (v_{xi}, v_{yi})^T$; $k_v, k_c, k_\varepsilon, k_\omega$ — parameter; $\mathbf{V}_i = (V_{xi}, V_{yi})^T$ — the speed of the center of gravity of the number i robot group in the coordinate system of the first robot. The position of the number i robot relative to the number i robot; d — the safety distance between the robots; $\mathbf{r}_{ij} = (x_{ij}, y_{ij})^T$ — the error of the number i robot relative to the specified current position; $\varepsilon_{\varphi i}$ — the error of the number i robot relative to the specified current position.

Computer verification of the algorithm. The behavior of the formation in the configuration change process is simulated in the stage_ros environment, forming a hierarchical structure of the control system software, which includes four levels, the upper layer-the escort aircraft operation interface (intelligent layer); the strategy layer and the tactical layer. The strategy layer's task is to determine the subtasks of each robot (the escort aircraft coordinator). The tactical layer's output is the robot movement control signal; the lower layer-the external environment and the robot's mode (execution layer). The computer simulation results (Fig. 8, see the second side of the cover) have demonstrated the performance of the proposed method.

Conclusion

This article introduces the solution to the robot group's target search, motion planning and control tasks during the earthquakes and studies the method of searching for victims using the device of probability theory. It developed an algorithm to construct the software trajectory of the main ground robot based on the map comparison with the accompanying UAV data and studies the behavior planning and coordination methods to ensure the change of the robot group's motion state. At the tactical level, it forms two modes of motion control, which are group reconstruction mode and configuration saved motion mode.

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