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Decentralized Control of a Group of Robots Using Fuzzy Logic

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Abstract: The purpose of this research is to develop and research a method to organize a formation of robots and a method to plan motion paths for a group of robots. The structure of a group control system for autonomous mobile robots is presented. We propose the solution for the problem of creation of a group formation with a scalable flexible structure. There is only minimal needed a-priori information that has the form of certain areas (attachment sites) around each robot that are appropriate for positioning of other robots. Setting the location of attachment sites around the robots makes it possible to organize various formation geometries. A context-depending strategy of behavior and fuzzy logic were used to implement the method of planning the behavior of individual robots in the group.

Key words: Robot, group control, planning, formation, path, fuzzy logic

INTRODUCTION

Modern robots are capable of solving various civil and military tasks including but not limited to monitoring different objects, cartography and mapping, performing rescue, recon and military missions, detecting forest fires, etc. One of the factors determining the degree of autonomy of Mobile Robots (MR) is the used control algorithms ensuring path planning, following and obstacle avoidance. The results successfully achieved by individual MRs in practical tasks can be improved by application of robot groups.

The solution of a group control task commonly faces with conflicting, contradictory and uncertain situations. The methods of fuzzy logic give a convenient tool for formalization of these situations. The idea of hierarchical fuzzy controller (Mac *et al*., 2015) is in the representation of the common behavior of robots as a composition of separate simple behaviors (models) organized in a hierarchy. Group control of mobile robots can be performed either using a robot-leader or without it.

Using the robot-leader results in a more coordinated motion of the robot group because it becomes possible to get a fuller picture of robot's location at every moment of time.

Hagras *et al*. (2010) have also solved the group control task using hierarchical controllers. The main difference from the work 1 is in the used mechanism of coordination of robots in the group which classifies current situations and assigns a role to each robot in the operational area.

The idea of the multiagent approach to robot group control is in distribution of control tasks among agents-coordinators each performing a strictly defined list of actions (Vadakkepat *et al*., 2007). Li *et al*. (2016) proposed the hybrid method for indoor MR path planning where the D-algorithm is used as a basis of the planning algorithm. To modify the planned trajectory in the conditions of environment disturbances an adaptive fuzzy controller was used.

Manoj proposes a method that makes it possible to plan the motion paths of robots in a group for environments with obstacles (Manoj, 2014). An optimal trajectory is selected out of a variety of possible ones using fuzzy estimations formed by a fuzzy controller. There is a method for a collective control of a group of robots moving to a goal which is special due to a prognosis of the goal spatial position (Sariff and Wahab, 2014). Hybrid path planning in a non-deterministic environment also can be based on a fuzzy controller and an artificial neural network (Rulong *et al*., 2011).

In the researches mentioned above and other known researches on mobile robots control little attention is paid to such an important problem as organization of a group formation and maintaining it during the motion to a goal. It is important in missions that include rescue operations where effective organization of the group formation and motion is of crucial importance for a successful mission.

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MATERIALS AND METHODS

Structure of robot group control system: It is proposed to use the principle of distributed control illustrated in Fig. 1a for creation a mobile robot group control system. Control decisions are made independently by the Control System (CS_i) of each autonomous robot R_i basing on data S_i received from the sensor system and data C_R, that is composition of $C_{\Re}$ (data received from other robots) and C_{Ri} (data transmitted by the robot R_i to other robots). The Control System (CS_i) forms the control signals U_i for the robot actuators which affect the environment E through the actions A_i to achieve the group goal G. Influence of the environment E on the R_i is denoted by E_i.

The control system CS_i can be presented in a form of the hierarchical structure shown in Fig. 1b. At the strategic control level, it solves the tasks of goal assignment, determining the ways to reach the goal, formation of groups and their structure. At the tactical control level, the following tasks are to be solved:

- Determining the robots own position
- Planning the trajectory to the goal according to data S_i and data $C_{\Re}$ received from other robots
- Control of the robot motion along the planned path

At the execution level, the control signals for the robot actuators are calculated. In Fig. 1, $\eta = \{\eta_1, \eta_2, ...\}$ is the set of communication channels between this robot and the other in the group; x^*_d is the corrected vector of generalized coordinates of the next path point for the robot R_i; x^*_g are the generalized coordinates of the selected goal. At the strategic control level the formation creation is carried out, the goal coordinates are calculated and neighboring robots are allocated. The path is planned to the point with coordinates x^*_g. In the position-path controller block of the tactical control level the control signals for the robot actuators are generated. They ensure its motion along the found path to the pre-set point (Pshikhopov *et al*., 2014). Let's take a closer look at the formation creation and path planning.

Group formation problem: Having a minimal amount of a-priori information, the group formation procedure should ensure scalability and flexibility of the formation's structure. We use the allocation of certain areas (attachment sites) Ω_i around each robot (Balch and Hybinette, 2000) where other robots can be positioned as it is shown in Fig. 2a.

Different arrangements of the attachment sites Ω_i around the robots allow various formation geometries (Fig. 2b) depending on the distance l from the robot to the sites Ω_i and their offset angles ψ. Let's introduce the grid templates of n×m size. This will give us the possibility to achieve more flexible formation shapes and to change the formation geometry dynamically. The examples of grid templates are shown in Fig. 3.

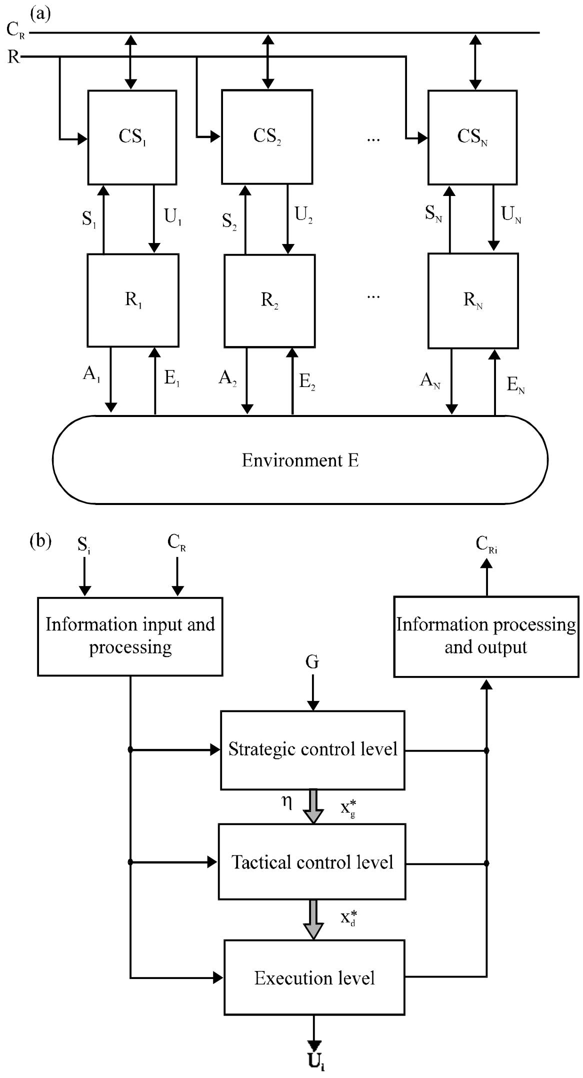

Fig. 1: a) Structures of group control system and b) robot R_i control system

IDs are assigned to the robots for regulation of their interactions in the formation. The robots with larger IDs are guided by the robots with smaller IDs (leaders). All robots need to know a current template and a relation between IDs of the robots and the template. If a robot loses its leader, it selects a new leader-the one that was a leader for the lost robot.

At the first stage of the formation creation each robot finds a leader for itself and transmits its ID to the leader.

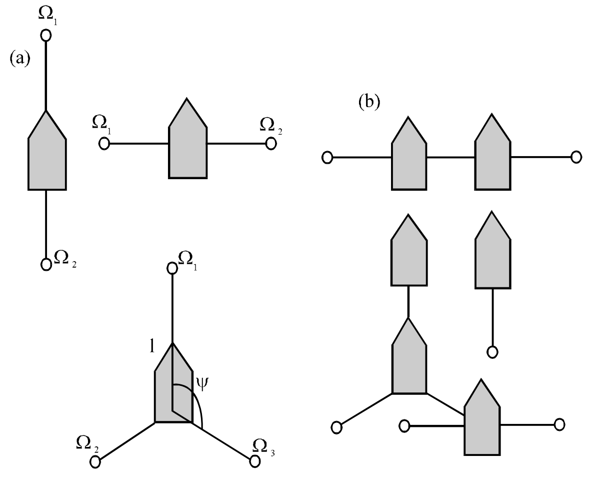

Fig. 2: Various possible locations of attachment sites Ω_i around robots

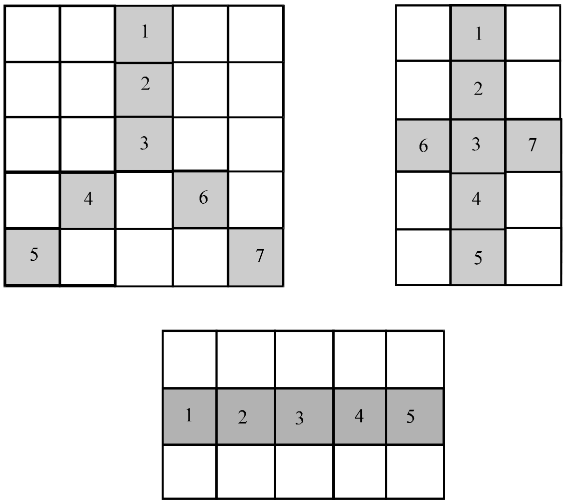

Fig. 3: Grid templates of formation structure

At the second stage, each robot-leader calculates the offset angles and distances to the attachment sites and sends this data to its following robots.

During the motion in space each MR either determines the current coordinates and offset angles of its robot-leader or requests these parameters form the leader and then calculates the parameters of attachment sites Ω_i. This allows reduction of the leader's onboard computers computational load. The robot-leader can have several following robots and it is possible to delegate them a part of calculations.

Each of the following robots treats the sites Ω_i as the goals to move. Each robot performs spatial orientation, just like its leader in order to move in a formation and to maintain it. In order to change the formation geometry during motion, it is necessary just to change the used template.

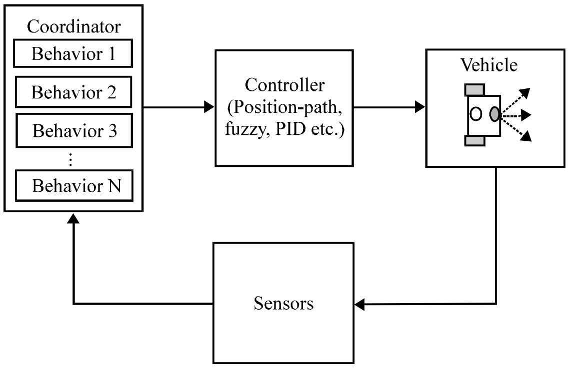

Fig. 4: Fuzzy planner structure

Robot motion control: We used the idea of the method (Wang *et al*., 2011) according to which the overall behavior of the robot is split into a number of simpler ones such as "motion to goal; obstacle avoidance; wall-following", etc. In the process of our researching we eliminated the "wall-following" behavior and the "emergency situation" behavior because of their insufficient effectiveness and irrelevance to the robot safety.

The fuzzy planner structure is presented in Fig. 4. In the motion process, the sensor system ensures obtaining the necessary information about obstacles location for each behavior_i controller. Basing on sensor data and control rules each behavior controller determines the desired robot velocity and motion direction. And then, coordinator combines output variables of each behavior controller.

Detection of an obstacle position with respect to the robot is based on the sector representation of environment as it is shown in Fig. 5. In comparison to literature 10, we reduced the number of used sectors. This simplifies the structure of control rules and controllers. Orientation of the robot with respect to the goal is based on using a special value θ_{error} being the difference between the direction of the robot longitudinal axis and the vector directed to the goal. The term set for the linguistic variable "orientation error" θ_{error} of the fuzzy controller "motion to a goal" is:

$$T(\theta_{error}) = \{\text{N-Negative; SN-Small Negative; Z-Zero; SP-Small Positive; P-Positive}\}$$

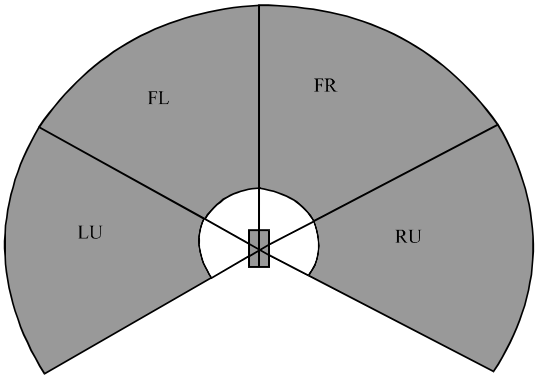

Fig. 5: Sectors of MR neighborhood; FL, FR-Front Left and Front Right sectors of the MR neighborhood; LU, RU-Upper Left and Upper Right sectors of the MR neighborhood

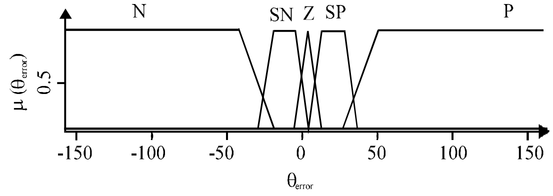

Fig. 6: Term set of LV θ_{error}

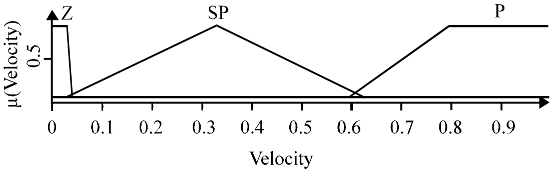

Fig. 7: Term set of LV Velocity

The values of robot velocity, its steering angle, distances to the obstacles and to the goal are also presented in a form of term sets. The term sets of the linguistic variables "orientation error" and "velocity" are presented in Fig. 6 and 7. The distances to obstacles and to the goal are given by the value D. Representation of D as a term set of the Linguistic Variable (LV) of the fuzzy controller "motion to a goal" has the following form:

T(D) = {N-Near; M-Medium; F-Far}

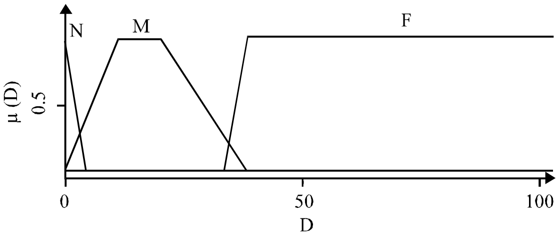

Fig. 8: Term set of LV D

Table 1: Fragment of the control rules base for "obstacle avoidance" model

	Input variables				Output variables	
Rule No.	RU	FR	FL	LU	Steering	Velocity
1	F	F	N	F	R	Z
2	F	F	M	F	R	SP
3	F	N	F	F	L	Z
4	F	M	F	F	L	SP
...						
27	F	F	M	N	RF	Z
28	N	N	N	F	L	Z
29	F	N	N	N	R	Z
30	N	N	M	F	LF	Z

The membership functions for the elements of the term set of the LV T(D) are presented in Fig. 8. The relation between the input and output values of the fuzzy controllers is set using bases of control rules. The fragment of the control rules base for the "obstacle avoidance" model is presented in Table 1. The main problem inherent in most of the behavior-based approaches is the necessity to design a coordinating unit activating a certain behavior at a certain time. We propose to use a coordination method that is different from the one proposed in literature 11. Here, we are going to use all the models of behavior simultaneously. The obtained angles and velocities will be merged using the following analytical expressions:

$$x_{i+1} = x_i + \sum_{j=1}^{N}\left(K_j V_j\right)\cos(\varphi_i + \frac{1}{N}\sum_{j=1}^{N}\Delta\varphi_j)\Delta t \quad (1)$$

$$y_{i+1} = y_i + \sum_{j=1}^{N}\left(K_j V_j\right)\sin(\varphi_i + \frac{1}{N}\sum_{j=1}^{N}\Delta\varphi_j)\Delta t \quad (2)$$

Where:

x_{i+1}, y_{i+1} = The MR new coordinates
x_i, y_i = TheMR current coordinates; V_j is the MR velocity

obtained from the jth behavior controller; φ_i is the MR current orientation angle; $\Delta\varphi_j$ is the change of the MR orientation angle obtained from the jth behavior controller; N is the number of MR behavior models; Δt is a time interval; K_j are weighing coefficients.

For each separate behavior basing on the set of control rules, the controller calculates the MR velocity V_j and the change $\Delta\varphi_j$ of the orientation angle for the current time moment. Calculation of the new MR coordinates x_{i+1}, y_{i+1} is performed by a weighed sum of the current coordinates x_i, y_i and the increment calculated using V_j and $\Delta\varphi_j$ obtained for each behavior. The weighing coefficients K_j allow the controller to take into account the influence of separate behaviors on the path planning process.

RESULTS AND DISCUSSION

Modeling was performed in MATLAB using the model of the 3-wheeled MR (Kalyaev *et al*., 2009). The distance to the attachment sites was 3 m. In Fig. 9, the results of formation creation and reconfiguration in the process of motion of the group of 5 robots can be seen. The goal had the coordinates (55, 55). The robots are shown as circles. The initial location and orientation of robots were set arbitrarily in the square 10×10 m attached to the point (0, 0) (Fig. 9a).

At the first stage the robots were to form a "column" formation as it can be seen in Fig. 9b and then continued motion in this formation. When the group leader reached the coordinate x = 25, the formation template was changed to "rank" (Fig. 9c) and after that the group continued motion to the goal (Fig. 9d).

When the formation is to be built during the motion, the leader has to keep its velocity lower than the velocity of other robots. The velocity can be increased to the maximal level after the formation is implemented. For the given initial conditions, the robot positioning error in the formation didn't exceed the value of 10 Sm (Soloviev *et al*., 2015).

Figure10 represents the simulation results for the robots moving in obstructed environment. The goal point is located at (55, 55). The obstacles (15 items) are shown as squares and located arbitrarily. The "wedge" formation was used. During their motion, the MR avoid obstacles trying to maintain the formation. To ensure a safe motion, the coefficient K_j in Eq. 1 and 2 for the "obstacle avoidance" model is greater than for the "motion to a goal" model. The safety radius was set to 0.25 m. When an obstacle was detected within the safety radius, the evasive maneuver was being initiated. After the robots passed the obstacles they reconfigured back into the initial formation and continued their motion to the goal.

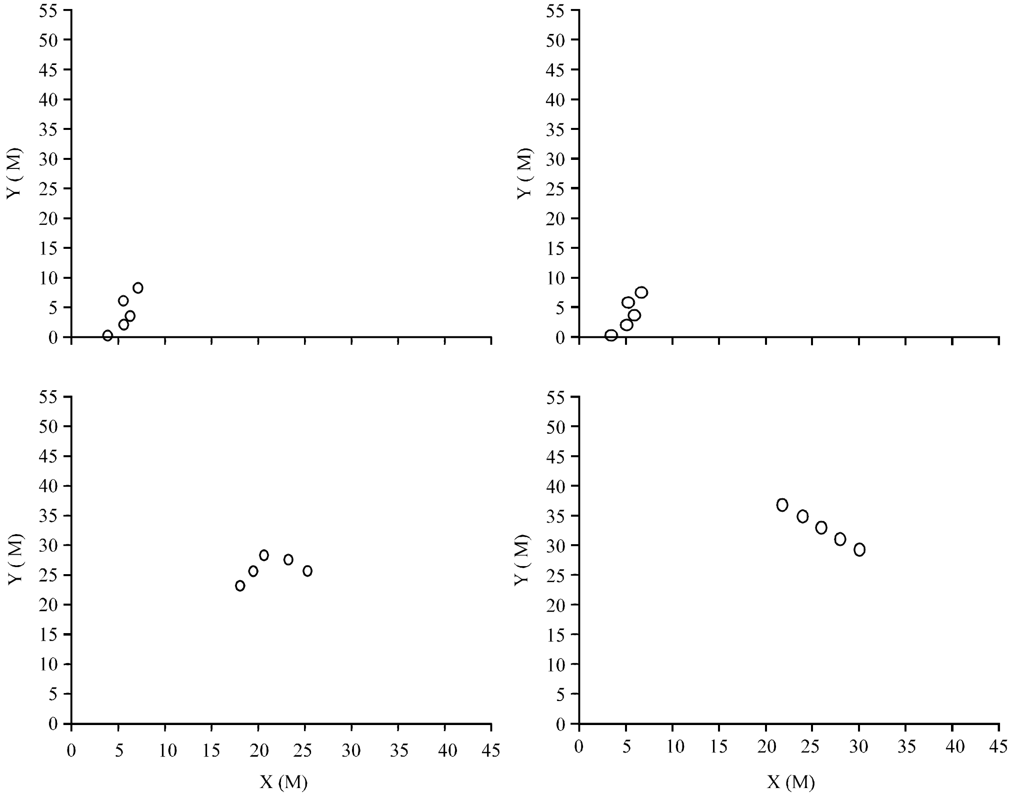

Fig. 9: Formation creation

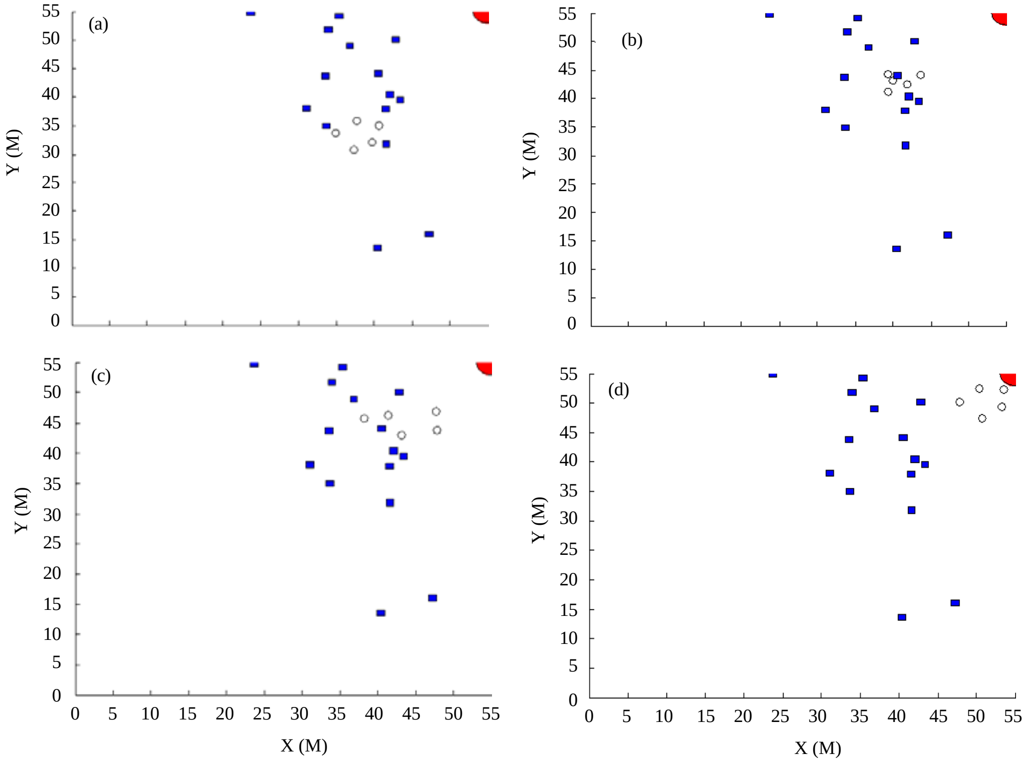

Fig. 10: Motion of robots in formation in obstructed environment

CONCLUSION

In this study, we presented the method to create group formations of robots using templates on a flat grid and the concept of attachment sites around robots. The advantage of this method is the small volume of a-priori information necessary for the creation of a formation. Existence of a template makes it possible for the robots to continue motion in the formation even in the case of the leader fault. Besides, if the group of robots is homogeneous, there is no need to assign the IDs to the robots in the template. They can be defined at the beginning of functioning basing on for example, analysis of the distance to the goal and the neighboring robots. The considered behavioral approach to the motion planning with application of fuzzy logic provides safe motion to the goal in obstructed environments. We are going to extend the approach on 3D obstructed environments.

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