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Formation Control of Heterogeneous Multi-Robot Systems

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Abstract: In this paper, a new position feedback based formation control method for heterogeneous multi-robot teams is presented and evaluated. The formation behaviors are integrated with dynamic reference object based collaborative navigation and efficient obstacle avoidance to maintain and change formation real-time. This method is computationally efficient and easy to coordinate in heterogeneous systems. The time to formalize and switch specified formation patterns can be controlled by adjusting the position feedback parameter. Satisfactory experimental results are obtained in simulation and real heterogeneous multi-robot system which consists of autonomous vehicles and legged robots.

1. INTRODUCTION

Formation control is an important issue in coordinated control for a group of autonomous robots, with broad applications from house security patrol to military missions. There are four conventional methods of formation control. The first method is Behavior-Based Strategy (e.g. Arkin (1998), Balch and Arkin (1998)), which places weightings on certain actions for each robot and the group dynamics emerge. The advantage is that the group dynamics contain formation feedback by coupling the weightings of different actions. However, it is difficult to describe the dynamics of the group and to guarantee the stability of the whole system. The second method is Leader-Following Strategy (e.g. Das et al. (2002)). It is easy to control multiple robots in a desired formation and it is suitable for describing the formation of robots. The disadvantage is that it is difficult to consider the ability gap in heterogeneous robot teams. The third method is Potential Field Approach (e.g. Leonard and Fiorelli (2001)). It is computationally inexpensive and easy to perform real-time control. The problem is that the design of a proper potential field function is difficult and local extremum exists. The fourth approach is Multi-Agent System Method (e.g. Fax and Murray (2004)) which applies graph theory based approaches to the design of closed-loop feedback laws, and Virtual Structure Strategy (e.g. Lewis and Tan (1997)) which proposes a control scheme for improving multiple mobile robots in formation. The advantage is that it is easy to prescribe formation strategy. The disadvantage of both methods is the difficulty in controlling mobile robots in formation with a decentralized system.

As far as we know, only a few of current formation control methods have paid special attention to heterogeneous multi-robot systems with feature that the robots in the system differ either in hardware or in software (e.g. Parker et al. (2004), Takahashi et al. (2004), Huang et al. (2006)). Taking dynamic environments and uncertainty external to the multi-robot system itself into account, heterogeneous systems with robots in different shapes and abilities are more applicable in real world applications than the systems with the same team members. However, challenges for efficient formation control of heterogeneous systems exist. First, it is important to coordinate the robots with different hardware and software so as to add robustness to the formation. In addition, the control method needs to be computationally inexpensive, taking the real-time response to the environment into consideration. Moreover, in respect of autonomous decentralized control, how to control robots in the most suitable formation considering the ability of the robot is another problem. Besides, communication is limited in dynamic environments, especially in the outdoor case.

In this paper, we present a new approach based on position feedback control that addresses all the challenges mentioned above for decentralized formation control of heterogeneous multi-robot systems. The approach enables teams of heterogeneous robots to efficiently and easily formalize and switch specified formation patterns in dynamic and unknown environments. Specifically, we consider the heterogeneous system that consists of robots with different sensing abilities. On the one hand, we propose a dynamic reference object based probabilistic self-localization method which use robots in the team as the landmarks, and implement a time-variable limit cycle based method for real-time obstacle avoidance. On the other hand, a formation control protocol is described with emphasis on the different sensing abilities among the heterogeneous teams. The time to formalize and switch specified formation patterns can be controlled by adjusting the position feedback parameter.

This paper is organized as follows. In the next section, we introduce the heterogeneous multi-robot system. In Section 3, we focus on the formation control protocol of the system. Then, in Section 4, we show the results of computer simulation and real robot experiments supporting the reliability of our techniques. We conclude in Section 5.

2. SYSTEM ARCHITECTURE

2.1 Heterogeneous Multi-Robot System

Consider a heterogeneous multi-robot system with N autonomous robots which are indexed as $R_1, R_2, \ldots, R_N$. Suppose that every robot of the system can send own position and receive positions of other robots among the team through wireless network. Let $x_i(t) = [x_i, y_i, \theta_i]^T \in \mathbb{R}^n$, where $i = 1, \ldots, N$, donate

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the position of robot i at time t. θ_i is the heading direction of the robot. Moreover, to emphasize the heterogeneous property of the system, we suppose that only limited number of robots (one or more) named as *independent robot*s can perform global self-localization and navigation individually by own sensors in dynamic environments, while other robots named as *dependent robot*s need to use collaborative approach to calculate own positions. In the concerned system, different to the leader-following

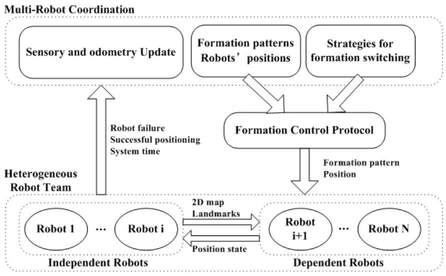


Fig. 1. System architecture. Suppose that there are i independent robots ($1 < i < N$) and $N - i$ dependent robots in the heterogeneous system.

model based approaches (e.g. Das et al. (2002)), only the independent robots that have high-accuracy sensors and high ability processors, are labelled uniquely, while the dependent robots have no label to identify. The diagram of the system architecture is briefly shown in Figure 1.

2.2 Collaborative Navigation

Taking the different sensing capabilities among the heterogeneous team into account, our position feedback based method of decentralized formation control relies on position calculation. However, only limited number of robots (independent robots) in the team have capabilities to perform relatively high-accuracy global self-localization and path planning individually. In this study, we propose a collaborative approach to help the dependent robots with low-accuracy sensors to formalize in certain pattern together with independent robots using relative position information. Sequenced-color markers for long distance recognition and single-color markers for short distance recognition are placed on the independent robots to help the dependent robots perform global self-localization.

Let us consider the case when the heterogeneous team is comprised of two independent robots (R_1 and R_2) and two dependent robots (R_3 and R_4), as shown in Figure 2. Similar to the probabilistic approaches for collaborative localization mentioned in (Wang et al. (2006)), we model the current position of the robot as the density of a set of particles which are seen as the prediction of the location. Initially, at time t, each location l has a belief:

$$Bel_t(l) \leftarrow P(L_t^{(0)} = l) \tag{1}$$

To update the belief of the possible location of the robot, at first, we use the new odometry reading o_t:

$$Bel_t(l) \leftarrow \int P(l|o_t, l^-) Bel_t(l^-) dl^- \tag{2}$$

If the robot receives new sensory information s_t, then it updates the belief with β being the normalizing constant:

$$Bel_t(l) \leftarrow \beta P(s_t|l) Bel_t(l) \tag{3}$$

Independent robots use the probabilistic approach to perform self-localization. However, in the heterogeneous system, dependent robots have to use the independent robots placed with markers as the dynamic landmarks, see Figure 2 for example, which can be considered as one case of the dynamic reference object based Markov localization mentioned in (Wang et al. (2006)). R_1 and R_2 are the independent robots equipped with

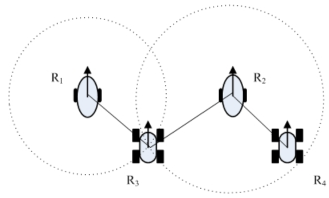


Fig. 2. Example of a heterogeneous multi-robot system comprised of independent robots and dependent robots.

two types of markers as the dynamic landmarks. Referencing on one type of the markers, the dependent robots can only get the distance to the markers but not the relative angle. The calculated distance is relatively accurate. If the dependent robots can see two markers at the same time or within a short period, they may update their positions refer to the independent robots with markers, see R_3 for example. Another type of markers is the one that robots can calculate distance and relative angle, which are accurate within limited areas. The dependent robots use the marker as reference to update the belief of possible location, see R_4 for example. With the independent robot R_j recognized as a dynamic landmark, the dependent robot R_i updates own position belief as follows with a normalizing constant η:

$$Bel_t^{(i)}(x_i(t)) \leftarrow \eta Bel_t^{(i)}(x_i(t)) P(x_i(t)|r_t) Bel_t^{(j)}(r_t) \tag{4}$$

where r_t is the position of the identified independent robot.

2.3 Real-Time Obstacle Avoidance

Real-time obstacle avoidance is an essential part of formation control of real-world heterogeneous multi-robot systems. In this study, we introduce a time-variable limit cycle based approach to help robot perform real-time obstacle avoidance. The shape of an obstacle is modeled as a cycle in the two-dimensional plane. Consider the following nonlinear system:

$$\begin{aligned} \dot{\tilde{x}} &= \rho(\tilde{y} + \gamma\tilde{x}(\bar{v}^2 - \tilde{x}^2 - \tilde{y}^2)) \\ \dot{\tilde{y}} &= \rho(-\tilde{x} + \gamma\tilde{y}(\bar{v}^2 - \tilde{x}^2 - \tilde{y}^2)) \end{aligned} \tag{5}$$

where ρ is the character factor of the obstacle which is set to be a positive value. γ is the convergence factor. Different obstacles may have individual ρ and γ. Here, $\bar{v}$ is the relative velocity to the obstacle which is dynamic when the robot moves. Note that $\bar{v} \neq 0$ because when $\bar{v} = 0$ there is no need to perform avoidance behavior. The size of the limit cycle is changing when system (5) switches. To prove that the circle $\tilde{x}^2 + \tilde{y}^2 = \bar{v}^2$ is the dynamic limit cycle of the switched system (5), we use the common Lyapunov function:

$$V(\tilde{x}, \tilde{y}) = \tilde{x}^2 + \tilde{y}^2 \tag{6}$$

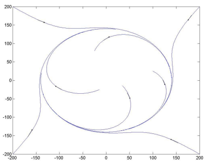
such that:

$$\dot{V}(\tilde{x}, \tilde{y}) = 2\rho\gamma(\bar{v}^2 - \tilde{x}^2 - \tilde{y}^2)(\tilde{x}^2 + \tilde{y}^2)$$

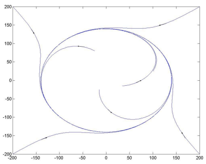
For limit cycle, we can see that $\dot{V}(\tilde{x}, \tilde{y}) < 0$ when $V(\tilde{x}, \tilde{y}) > \bar{v}^2$, while $\dot{V}(\tilde{x}, \tilde{y}) > 0$ when $V(\tilde{x}, \tilde{y}) < \bar{v}^2$. This shows the following region is absorbing.

$$B = \{\rho_1 \leq V(\tilde{x}, \tilde{y}) \leq \rho_2, |0 < \rho_1 < \bar{v}^2, \rho_2 > \bar{v}^2\} \tag{7}$$

Since this argument above is valid for any $0 < \rho_1 < \bar{v}^2$, and $\rho_2 > \bar{v}^2$, when ρ_1, ρ_2 get close to $\bar{v}^2$, region B shrinks to the circle $V(\tilde{x},\tilde{y}) = \bar{v}^2$.This shows that the circle is a periodic orbit as shown in Figure 3(a) when $\bar{v} = 280$, $\rho = 0.01$, $\gamma = 0.0001$. This periodic orbit is called a limit cycle. We can see that the trajectory from any point $(\tilde{x},\tilde{y})$ moves toward and converges to the limit cycle clockwise when close.



(a) clockwise



(b) counterclockwise

Fig. 3. Phase portrait of limit cycle.

The counterclockwise condition can be derived by the following system (shown in Figure 3(b)):

$$\begin{aligned} \dot{\tilde{x}} &= \rho(-\tilde{y} + \gamma\tilde{x}(\bar{v}^2 - \tilde{x}^2 - \tilde{y}^2)) \\ \dot{\tilde{y}} &= \rho(\tilde{x} + \gamma\tilde{y}(\bar{v}^2 - \tilde{x}^2 - \tilde{y}^2)) \end{aligned} \tag{8}$$

Consider that the trajectory from any point $(\tilde{x},\tilde{y})$ inside the limit cycle moves outward the cycle, and the trajectory from any point $(\tilde{x},\tilde{y})$ outside the limit cycle approaches the cycle with distance determined by the relative speed $\bar{v}$. The limit cycle provides a method for obstacle avoidance among multiple mobile robots which can be considered as dynamic obstacles, and objects in the environment which is static. When the robot is in a safe region, by the dynamic limit cycle approach, it will move away the obstacle toward the safe circle with a radius related to the speed of the obstacle. Let θ_0 denote the orientation of the obstacle, (x_0, y_0) the center point of the obstacle. With the following transformation, we get the expression of system (5) in the original frame:

$$\begin{aligned} x_i &= \cos\theta_0(\tilde{x} + x_0) - \sin\theta_0(\tilde{y} + y_0) \\ y_i &= \sin\theta_0(\tilde{x} + x_0) + \cos\theta_0(\tilde{y} + y_0) \end{aligned} \tag{9}$$

Let v_i denote the translational velocity of robot i in the original frame, while θ_i is the direction of the motion. The kinematic model of the robot is described by:

$$\begin{aligned} \dot{x}_i &= v_i \cos\theta_i \\ \dot{y}_i &= v_i \sin\theta_i \end{aligned}$$

Then we can see:

$$\begin{aligned} v_i &= \sqrt{\dot{x}_i{}^2 + \dot{y}_i{}^2} \\ \theta_i &= \arctan\frac{\dot{y}_i}{\dot{x}_i} + \theta_0 \end{aligned}$$

Different obstacles have their own characters, with ρ matching to characters respectively. Using ρ in different values can control the magnitude of the absolute speed.

3. FORMATION CONTROL PROTOCOL

In this section, we introduce a position feedback control protocol integrated with landmark recognition validity function to implement in formation control of heterogeneous teams.

Definition 1. The landmark recognition validity of robot i at time t is the estimate of the reliability and accuracy of landmark recognition. The validity function is denoted as $q_i(t)$ that satisfies $0 < q_i(t) < 1$.

Definition 2. Operator $\cdot$ between the landmark recognition validity $q_i(t)$ and position $x_i(t)$ of robot i is defined by:

$$q_i(t) \cdot x_i(t) = \begin{bmatrix} (1+\alpha e^{-q_i(t)})x_i \\ (1+\alpha e^{-q_i(t)})y_i \\ (1+\alpha e^{-q_i(t)})\theta_i \end{bmatrix}, \; i = 1,2,\ldots,N$$

where α is the heterogeneous factor that satisfies $-1 < \alpha < 1$.

Note that the value of the constant α may be different among the robots of the team, taking the different abilities of sensors equipped on the robots into account. Specifically, if the robot that can recognize landmarks in the dynamic environment better, we can set certain α to make $1+\alpha e^{-q_i(t)} \approx 1$, which means the robot can almost rely on the self-localization results. If the robot with relatively unprecise sensors, α can be modified to make the value of $1+\alpha e^{-q_i(t)}$ in a certain range based on the localization tests of individual robot.

Denote $\bar{x}_i(t) = q_i(t) \cdot x_i(t)$, where $i = 1,2,\ldots,N$. Let $X_t = [\bar{x}_1(t), \bar{x}_2(t), \ldots, \bar{x}_N(t)]^T \in \mathbb{R}^{Nn}$, where $t = 0,1,\ldots$, denote the system state at time t.

Definition 3. Given any $f_i \in \mathbb{R}^n$, $i = 1,\ldots,N$, where $f_i \neq f_j$, $i \neq j$, denote $f = [f_1, f_2, \ldots, f_N]^T \in \mathbb{R}^{Nn}$ as a candidate *formation*. We say that a multi-robot system is *in formation* f at time t, if there is a constant vector $c \in \mathbb{R}^n$ such that $X_t - 1_M \otimes c = f$. We say that a multi-robot system is *converged to the formation* f, if there is a constant vector $c \in \mathbb{R}^n$ such that $\lim_{t\to\infty}(X_t - 1_M \otimes c) = f$. Here, $\otimes$ is the Kronecker product.

In the following paragraphs, we discuss the formation control process of the concerned heterogeneous multi-robot system. Initially, the system is in state X_0. When $t = 1$, robot R_1 holds still and broadcasts own position to other robots in the system. When other robots receive the position, they move to the new positions by the protocol as follows:

$$\bar{x}_i(1) = \bar{x}_i(0) + \varepsilon((\bar{x}_1(0) - f_1) - (\bar{x}_i(0) - f_i)), \; i = 2,\ldots,N \tag{10}$$

where ε is a feedback control parameter to tune the magnitude of the feedback. Thus, the position of the whole system is adjusted to:

$$X_1 = X_0 + \varepsilon \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 1 & -1 & 0 & \cdots & 0 \\ 1 & 0 & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & \cdots & -1 \end{bmatrix} \otimes I_n(X_0 - f)$$

Denote

$$L_1 = \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 1 & -1 & 0 & \cdots & 0 \\ 1 & 0 & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & \cdots & -1 \end{bmatrix} \otimes I_n$$

Then we have

$$\begin{aligned} X_1 &= X_0 + \varepsilon L_1(X_0 - f) \\ &= (I_M + \varepsilon L_1)X_0 - \varepsilon L_1 f \end{aligned} \tag{11}$$

When $t = 2$, robot R_2 holds still and broadcasts self position to other robots in the system. When other robots receive the position, they move to the new positions by the protocol as follows:

$$\bar{x}_i(2) = \bar{x}_i(1) + \varepsilon((\bar{x}_2(1) - f_2) - (\bar{x}_i(1) - f_i)),\ i = 1, 3, \ldots, N \tag{12}$$

Then the position of the whole system is adjusted to:

$$X_2 = X_1 + \varepsilon \begin{bmatrix} -1 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & 0 & \cdots & -1 \end{bmatrix} \otimes I_n (X_1 - f)$$

Denote

$$L_2 = \begin{bmatrix} -1 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & 0 & \cdots & -1 \end{bmatrix} \otimes I_n$$

Then we have

$$\begin{aligned} X_2 &= X_1 + \varepsilon L_2 (X_1 - f) \\ &= (I_M + \varepsilon L_2) X_1 - \varepsilon L_2 f \end{aligned} \tag{13}$$

Repeat the similar process from R_3 to R_N. At time $t = N$, robot R_N holds still and broadcasts its position to others. Once other robots receive it, they move to the new positions by the protocol as follows:

$$\bar{x}_i(N) = \bar{x}_i(N-1) + \varepsilon((\bar{x}_N(N-1) - f_N) - (\bar{x}_i(N-1) - f_i)) \tag{14}$$

where $i = 1, \ldots, N-1$. Then the system state is updated by

$$\begin{aligned} X_N &= X_{N-1} + \varepsilon L_N (X_{N-1} - f) \\ &= (I_N + \varepsilon L_N) X_{N-1} - \varepsilon L_N f \end{aligned} \tag{15}$$

where

$$L_N = \begin{bmatrix} -1 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & 0 & \cdots & -1 \end{bmatrix} \otimes I_n$$

From time $t = N+1$, the system repeats the above procedures periodically. Thus, we can derive that the system state updating equation is given by:

$$X_t = X_{t-1} + \varepsilon L_{r(t)} (X_{t-1} - f) \tag{16}$$

where $L_i = (-I_N + E_i) \otimes I_n$. E_i is a $N \times N$ matrix defined as follows where the column i is 1 and others are all 0:

$$E_i = \begin{bmatrix} 0 & 0 & \cdots & 1 & \cdots & 0 \\ 0 & 0 & \cdots & 1 & \cdots & 0 \\ 0 & 0 & \cdots & 1 & \cdots & 0 \\ 0 & 0 & \cdots & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & \cdots & 0 \end{bmatrix}_{N \times N}$$

$r(t)$ is a periodic function defined as follows:

$$r(t) = \begin{cases} t, & 0 \le t \le N \\ t - iN, & iN < t \le (i+1)N \end{cases} \tag{17}$$

where $i = 1, 2, \ldots$.

Definition 4. Every robot in the multi-robot system adjust own position by using the dynamic equation defined in (16). We say that the system state updates one period, if everyone of the system complete own position adjustment.

To obtain the analytical solution of (16), let:

$$Z_t = X_t - f \tag{18}$$

Then

$$\begin{aligned} Z_t &= X_t - f \\ &= X_{t-1} + \varepsilon L_{r(t)} (X_{t-1} - f) - f \\ &= Z_{t-1} + \varepsilon L_{r(t)} Z_{t-1} \\ &= (I_N + \varepsilon L_{r(t)}) Z_{t-1} \end{aligned}$$

We can obtain:

$$Z_t = (\prod_{i=1}^{t} (I_N + \varepsilon L_{r(i)})) Z_0 \tag{19}$$

Derive from (18) and (19), we can get:

$$X_t - f = (\prod_{i=1}^{t} (I_N + \varepsilon L_{r(i)})) (X_0 - f) \tag{20}$$

Then

$$X_t = (\prod_{i=1}^{t} (I_N + \varepsilon L_{r(i)})) (X_0 - f) + f$$

Denote

$$A_t = (\prod_{i=1}^{t} (I_m + \varepsilon L_{r(i)})) \otimes I_n$$

Then the exact solution of (16) is given by

$$X_t = A_t (X_0 - f) + f, t = 1, 2, \ldots. \tag{21}$$

For this formation control strategy, we have the following strict convergency conclusion.

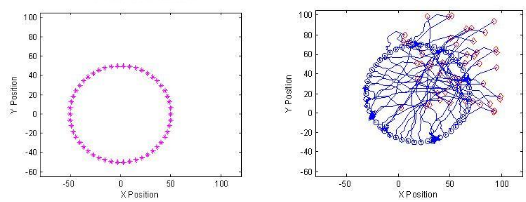
Theorem 1. For a multi-robot system, if the feedback gain ε satisfies $0 < \varepsilon < 2$, then there exists a constant vector $c \in \mathbb{R}^n$ such that the solution (21) satisfies that $\lim_{t \to \infty} (X_t - 1_N \otimes c) = f$, i.e., the system is converged to the formation f.

Note that Theorem 1 can be proven by mathematical induction.

4. EXPERIMENTAL RESULTS

4.1 Computer Simulation

In the first simulation, we considered a system consisted of fifty robots. Initial positions of the robots are randomly selected. We use the feedback control parameter $\varepsilon = 0.2$. To make the system heterogeneous, a random number in the range from 0.1 to 0.8 and a random number in the range from -0.2 to 0.2 are used to be the landmark recognition validity $q_i(t)$ and the heterogeneous factor α respectively. Fig. 4(a) is the

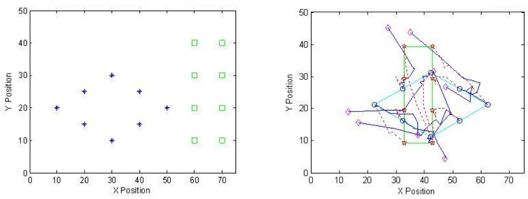


(a) (b)

Fig. 4. Formalizing certain formation pattern.

supposed final formation, where the red stars represent the position of robots. Fig. 4(b) shows the process of generating circle formation, where the red "◇" and blue "○" represent the initial and final positions respectively. After 50 periods, the system achieves the circle formation. With ε increasing ($0 < \varepsilon < 2$), there will be less period to achieve formation. If $\varepsilon = 1$, it takes only one period to achieves formation, which can be considered as a special case that is similar to the common leader-following method.

In the second simulation, we considered a system of eight robots to switch formation from a rectangle to a diamond. The landmark recognition validity $q_i(t)$ and the heterogeneous factor α are the same with the first simulation. Fig. 5(a) describes the supposed formations. As shown in Fig. 5(b), robots start from randomly selected positions marked pink "$\diamond$". First, they achieve a rectangle as shown in red stars. Then they change formation to a diamond as shown in blue "$\circ$". The feedback control parameter $\varepsilon = 0.25$. Note that in simulations, there is



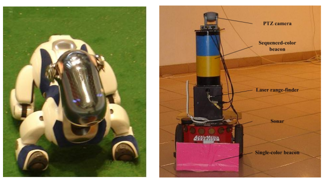
(a) (b)

Fig. 5. Changing formation from a rectangle to a diamond.

no consideration of obstacle avoidance during the process of formalizing certain pattern. In real robot experiments, robots perform real-time obstacle avoidance by the proposed method.

4.2 *Formation Control of Real Multi-Robot Systems*

In the real robot experiments, we considered a team of two Pioneer 2DX robots (see Fig. 6(b)) equipped with laser rangefinders, sonar, a pan-tilt-zoom (PTZ) camera and wireless device, and two Aibo robots (see Fig. 6(a)) equipped with a limited-view CCD camera and wireless device. We set the Pi-

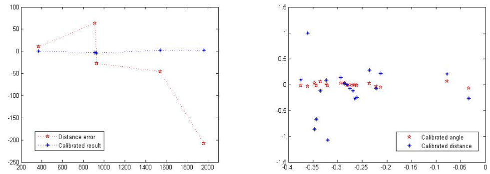


(a) (b)

Fig. 6. Robots in the experiments.

oneer robots as the independent robots and Aibo robots as the dependent robots. The two independent robots have different sequenced-color markers and single-color markers which are illustrated in Fig. 6(b).

Sensing Abilities To represent the difference in sensing abilities among the heterogeneous team, we should find the proper heterogeneous factor α. Initially, we set the independent robots in the team to stand at random positions and send estimated own locations. Then we manually calculate the real position. Since the high accuracy sensors, the localization results of the independent robots are relatively precise (say error of x and y within $20mm$ and error of θ within $0.1rad$). Thus, we choose $\alpha = 0.03$ that satisfies $1 + \alpha e^{-q_i(t)} \approx 1$. Note that $q_i(t) \approx 1$, since the relatively high accuracy recognition of landmarks. The localization results of the dependent robots are relatively



(a) (b)

Fig. 7. Determination of the heterogeneous factor α.

inaccurate (see the red line with pentacle points in Fig. 7(a) for example). Different dependent robots estimate own position at the same location may be different. Then we estimate proper α for the dependent robots. Similar to independent robots, we first put dependent robots at random position with more than one independent robots in the view. Then the dependent robots send own estimation of self-location. Comparing with real positions, we can get the errors in distance and angle. Next, we use one of the Aibo robots to illustrate how to find α in a proper range. For this robot, the estimate distance and angle are always bigger than real ones, α can be set less than 0. And the max proportional error is under 0.5. Then we select α randomly in the range from -0.4 to 0 to find the calibrated results. From Fig. 7(b), it is clear that α in the range from -0.35 to -0.25 can result low-error position estimations. Thus in the real robot system, we use α as a random number in the range from -0.35 to -0.25 for this Aibo robot. The blue line with star points in Fig. 7(a) shows the result after calibration. After finding proper α for all the dependent robots, formation control results of heterogeneous multi-robot system may be improved.

Formation Control In this experiment, with proper heterogeneous factor α, we evaluated the proposed approach and compared the results of systems with or without emphasis on different sensing abilities. The global coordinates of the four robots R_1, R_2, R_3, R_4 (see Fig. 9(a)) are notated as (x_1, y_1), (x_2, y_2), (x_3, y_3), (x_4, y_4). Robots move to certain diamond formation, where R_1 and R_4 are in the beginning and ending of one diagonal of the diamond respectively while R_2 and R_3 are on the other diagonal. To measure the influence on formation, a performance function F is defined by using the characteristics of a diamond:

$$F = arctan(\frac{y_4 - y_1}{x_4 - x_1}) + arctan(\frac{y_3 - y_2}{x_3 - x_2})$$

where *arctan* is the arc tangent function. If the value of F gets $90°$, we say that the diamond formation is achieved. Our approach is applied to this multi-robot system. We use a computer to receive and measure the convergence of the formation. Fig. 8 shows the comparison of systems with or

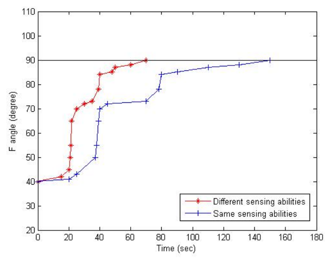


Fig. 8. Comparison of heterogeneous systems with or without emphasis on different sensing abilities.

without emphasis on different sensing abilities. The red line is the convergence result of our proposed method with proper heterogeneous factors for different robots. The blue line is the result of using the same α (say $1+\alpha e^{-q_i(t)}=1$). It is clear that the red line first gets the best performance that the system achieves a diamond formation. Based on the navigation method described in Section 2, the test heterogeneous team can formalize and switch specified formation patterns. Fig. 9 shows

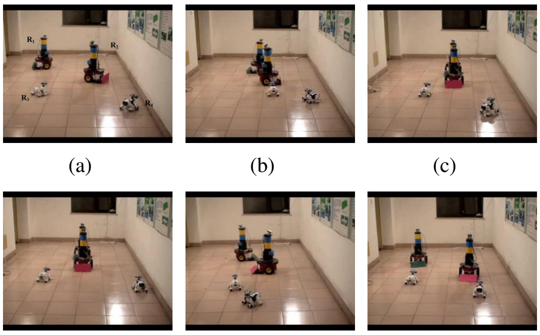

(a) (b) (c) (d) (e) (f)

Fig. 9. Formalizing and switching specified formation patterns.

the formation control process. Initially, four robots are placed at randomly selected positions, facing to the wall. The robot team first performs a triangle formation (see Fig. 9(d)). Then it switches to a diamond formation (see Fig. 9(f)). The proposed real-time obstacle avoidance method guarantees the robots to walk to expected positions with no collision.

Navigation in Formations In order to evaluate the performance of the proposed formation control method for heterogeneous multi-robot systems in more complex scenarios, we additionally performed experiments in a corridor environment with certain obstacles as shown in Fig. 10. First, a team of

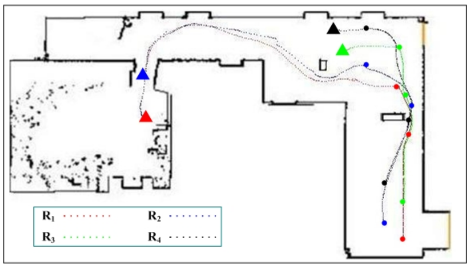


Fig. 10. Trajectories of the four robots to navigate in formations using our approach.

two independent robots (Pioneer robots) starts from point A and B which are in our lab adjacent to the corridor. Then the robots walk through the corridor and avoid the obstacle placed in point C (see Fig. 11(a)) using the proposed method mentioned in Section 2.3, to meet the two dependent robots (Aibo robots) which wait around point D (see Fig. 11(b)). After that, the system converts into a heterogeneous system. During this period, the four robots formalize a diamond formation and walk forward through the corridor (see Fig. 11(c)). The independent robots use laser range-finders to detect obstacles in the way. When the obstacle placed in point E is detected, the team switch formation into a line (see Fig. 11(d)(e)) to walk through the narrow way between obstacle and wall. The dependent robots use the positions of the independent robots as reference. When the last robot passes the narrow way (see Fig. 11(e)), it broadcasts to the teammates that the whole team has successfully avoided the obstacle. Then the team reconstructs the diamond formation (see Fig. 11(f)). The team walks to the point F as the destination. The path length from the start to the destination is nearly $25m$. This experiment has implemented in the heterogeneous team with emphasis on sensing abilities. It took 100-120 seconds after the start of an experiment.

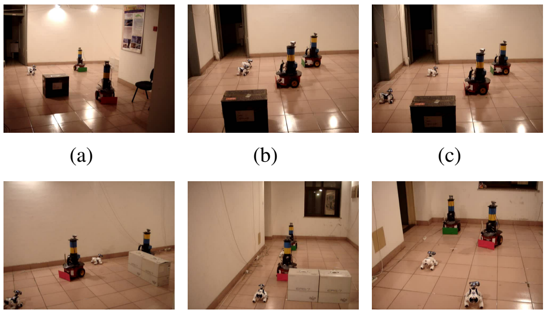

(a) (b) (c) (d) (e) (f)

Fig. 11. Navigation in formations.

5. CONCLUSION

In this paper, we have demonstrated a new approach based on position feedback control for decentralized formation control of heterogeneous multi-robot systems. The approach enables teams of heterogeneous robots to formalize and switch specified formation patterns efficiently and easily in dynamic and unknown environments. In the future, experiments will be continued in outdoor environments with more complex heterogeneous multi-robot systems.

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