TEAM-ORIENTED FORMATION CONTROL FOR MULTIPLE MOBILE ROBOTS

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Abstract: This paper addresses on the team-oriented task description and its usage in the mobile robots formation. The team behaviour module is introduced for the team-level task description and the temporal chain of these modules is used to define the team trajectory. The team shape is expressed as a low-triangular matrix by the graph theory to express the lead-follow relation in the formation and the shapes switching is based on the selection of the optimal transition matrix. The experiment of a heterogeneous robots team formation testifies the efficacy.

Keywords: Mobile robots, Robot control, Transition matrices

1. INTRODUCTION

There are many intractable problems in mobile robots control, such as optimal path planning and hostile environmental detecting. These issues cannot be settled well only by the robots intelligence because current robots cannot analyze and make decisions for complex events effectively. Well-designed human-robot interactive system is a key aspect in practical application of the multi-robots system (MRS). In traditional robot software development, textual programming languages, such as C++ and LISP, are used to specify tasks. These text-based software design processes, which require highly trained programmers and long development time, meet with great embarrassment. Opposite to them, graphical tools offer an interface that users can send commands to robots typically with graph, flow chart or diagram while the status of robots is shown on the screen visually. It is easier to learn and use, which saves the time and cost. The representative robots programming system are Lego Mindstorms (Biggs and MacDonald, 2003), Onika (Gertz, *et al*, 1994) and MissionLab (Mackenzie, *et al*, 1997).

Although the previous researches did well in graphical programming, the software used in MRS should be better in the convenience usage especially the team-oriented task design. Team is an important concept in applications where sensor assets are limited, such as scouts, spacecrafts and Unmanned Ground Vehicles (UGV). In these cases, individual robot can concentrate its sensors on a part of the environment while other robots cover the rest (Balch and Arkin, 1998). The team also can be regarded as one unit when each member robot does same motion, e.g. formation.

In this paper, the team-oriented conception is provided in section 2 and its graphical programming tool is described in section 3. The formation control strategy is given in section 4 and section 5 is the experiment and results analysis.

2. TEAM-ORIENTED CONCEPTION

The robots team-oriented conception includes four parts, the hardware structure, the team coordinate space, the roles assignment and the Team Behaviour Module (TBM) definition.

2.1 Hardware Structure

Since most mobile robots support the Wireless Local Area Network (WLAN), the hardware structure is designed with this feature. Robots, regarded as intelligent agents, constitute nodes in WLAN, which transmit and receive data by means of radio frequency. They implement wireless communication

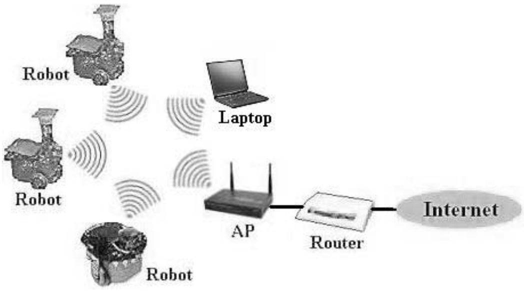

Fig. 1 The WLAN structure of the team

via wireless network card and access point (AP), which connects with the laptop directly or the Internet through a router. It reduces the line connection and enhances the flexibility. The WLAN structure of the team is shown in Fig. 1. The laptop in that figure is a terminal to realize the task description and real time inspection.

The experimental team is made up of Pioneer 2-DX and Frontier-I robots. Pioneer 2-DX is a kind of mobile robot fixed with PTZ camera, sonar arrays and odometer. Frontier-I is a medium-size autonomous robot from Shanghai Jiao Tong University (Jia, *et al*, 2004), on which an omni-direction vision sensor is equipped to detect the environment around. The colour based object identification method is adopted in Frontier-I, which can track eight colourful objects simultaneously.

2.2 Team Coordinate Space

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In order to describe the motion of the whole team, the relationship among robots positions should be analyzed clearly. For example, in formation the lead-follow strategy is often adopted to maintain the team shape. The leader robot has its own position, which is also a reference for the other robots. These positions are original values and other extra values such as relative angles between two robots can be calculated. The absolute and relative data constitute different coordinate frames. There are three frames in the space and all of them are shown in Fig. 2. The world frame *O-XY* is fixed in the real space while the values *R*1, *R*2, *R*3 (robots position) and *T* (the team position) are expressed under it. The robot frame located on the centre of the connecting line between two wheels while the positive direction of Y' axes is

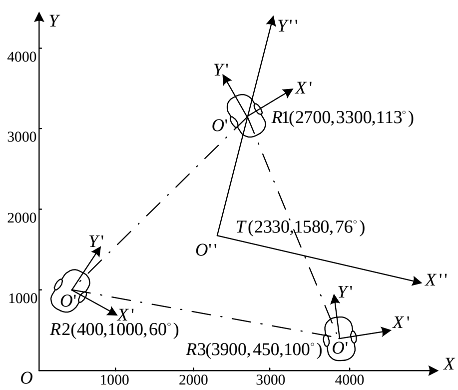

Fig. 2 Coordinate space of the team

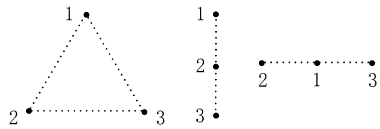

Fig. 3 Roles assignment in the team

pointed from the robot back to its nose. The third is the team coordinate frame $O'' - X''Y''$, in which the origin O'' is located on the centre of all the team members and the positive direction of Y'' axes is pointed to leader robot origin O'.

2.3 Roles Assignment

Inside the team, individual robots play different roles based on their ability or purpose. For example, in a transporting UGV team, the captain, who makes decisions and gives commands, is distinguished from its colleagues. In charge of the reconnaissance job, the robot in the forefront is also different with others. The introduction of the roles assignment achieves a hierarchical relationship in the team and a suitable roles system is benefit to the cooperation. Three robots roles defined in the typical formation shapes, diamond, column and line (Balch and Arkin, 1998), are shown in Fig.3. It is a position-related roles assignment system. Robot with role-1 is the leader of the team while the left two robots, role-2 and role-3, are followers.

Some studies on MRS also mentioned the team, but didn't discuss the roles function deeply. A team with roles assignment could exert the cooperation of the team because the members have a clear responsibility partition, which is one of the differences between an effective team and a simple sum of robots.

2.4 TBM Definition

The theoretical basis of TBM is the Societal Agent theory (MacKenzie, 1996), which describes the re-cursive composition of agents. For example, a trans-porting UGV troop marches across a plain. Based on the agent theory, each vehicle can be viewed as an agent *A*1 and the troop, congregated by all the vehicles, forms a high-level agent *A*2. *A*1 has a variety of behaviours, such as marching, danger detecting, obstacle avoiding and formation keeping. A2 has many behaviours too, e.g. formation, docking and wandering. The troop behaviours, independent of their particular individual behaviours, can be carried out at the troop-level without considering the details of each vehicle. That is to say, the behaviours of *A*2 has no direct relation with *A*1 even if *A*1 constitute *A*2.

TBM is just a team level behaviour set, which can be executed on the whole team especially the team is composed of different types of robots. TBM, realized by Finite State Automata (FSA) chains, contains two parts, states and triggers. Based on the set theory, three conclusions are drawn about the division of these sets:

Table 1 TBM definition

Type	Name	Description
State	Start/End	Start/End a task
State	Formate	Move from current position to terminal position with a specified shape
State	Wander	Move along a random trajectory
State	Seek	Seek a specified colourful object
State	Dock	Move to the House (a specified area to park robots)
Trigger	Immediately	Transition immediately
Trigger	AtGoal	Transition when the team arrives the specified position
Trigger	Find	Transition when specified object is found
Trigger	OverTime	Transition when specified seconds are passed
Trigger	Finished	Transition when previous state finished

1. Sets must include most ordinary states/ triggers.
2. Each state/trigger must be a standard and independent state/trigger.
3. Each state/trigger must have least overlap and most difference.

The definitions of primary states and triggers are shown in Table 1. In that definition, a state is the executing part of the task and a trigger is the transition among states. States and triggers appear in turns to finish the whole process. Operators can easily choose states and triggers to compose a TBM chain. In Table 1, 'Start' and 'End' are not FSA states in strict sense, but they are included to design a complete task. 'Finished' appears when its previous state is finished while 'AtGoal' happens when the team arrives its goal whether the previous state is finished or not.

3. TEAM DESCRIPTION TOOL

TBM is realized by a specially designed graphical programming tool, which is named Visual FSA Diagram (VFD). It can be used for the team description and task execution conveniently. Fig. 4 shows a task described by the VFD graph.

Icons represented VFD states and triggers are placed at the left of the figure. The main body of the figure is the design area to place the VFD chains, in which states and triggers are expressed as circle or rectangle diagrams. Users select wanted icons and place them in the VFD design area by clicking the mouse easily. Lines connecting the states and triggers are generated automatically when users click the two related diagrams while those diagrams will be filled with pink colour in turn at the executing time to show the

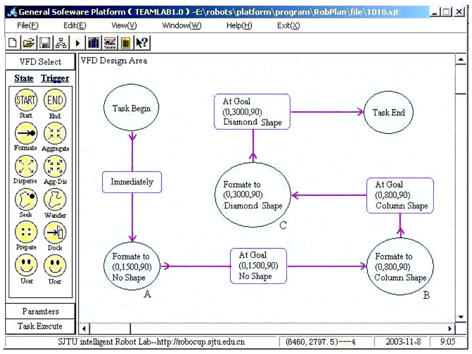

Fig. 4 A team-level task described by VFD graph

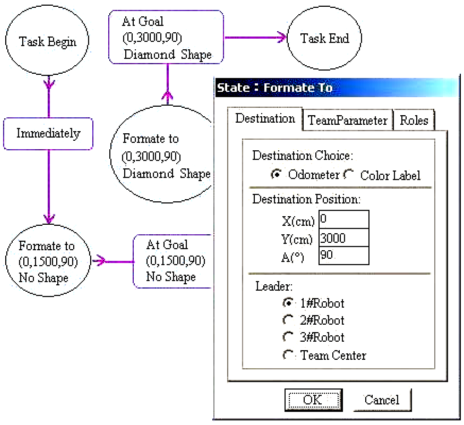

Fig. 5 Team VFD configuration

real time status. In Fig.4, robots go to a defined position from initial positions without team shape demanding (VFD-*A*) at first. Then they go to next destination with a column shape (VFD-*B*) and after arriving that position they change the team shape into a diamond one (VFD-*C*). The team trajectory can be controlled with the team position *T*, which is defined in Fig. 2. For example, in VFD-*B* 'Formate to (0,800, 90) Column Shape' means the target team position is $T(0,800,90^{\circ})$.

In VFD chains, the configuration method is introduced to modify parameters, which is shown in Fig. 5. This method, which is designed to support the team tasks, can describe the team information including member robots, the team type, the team position, the team leader, the robots roles and the inter-robots distance, etc.

4. FORMATION CONTROL

There are three approaches to MRS formation coordination reported in the literature, named leader-following (Desai, *et al*, 1998), behavioral (Balch and Arkin, 1998), and virtual structures (Lewis and Tan, 1997). In the MRS formation, robots must group together to form a given shape, if necessary to change that shape, during the process that they march from the original position to the destination. The formation control can be divided into three levels. The whole formation process can be divided into several sub-processes by the VFD states and formation switching is the strategy to describe the relation among them. It is the highest level in the formation and in the lower level is the basic formation control strategy, which forms the shape and marches to the destination. The robots individual control is the base of the team formation.

4.1 Formation Switching

For the formation with team shapes changed, there are two important problems, why to change shapes and how to change shapes. During the team navigation, robots may meet obstacles or the boundaries of the environment. The team must change its shape to pass by the areas safely. In this paper, a VFD module triggers the switching of team shapes.

Lead-follow relations among robots in the three typical formation shapes are shown in Fig.6. *R1* and *R3* have omni-direction cameras while *R2* has a fore-direction one. So *R3* can follow *R1* and *R2* while *R2* can only follows *R1*. The team shape is defined as a stable one only if the shape is symmetrical to the team orientation line and the team centre is also on that line. For three robots, the stable shapes are just the shapes in Fig.6. Every shape not the same as Fig.6, for example, the 'L' shape, is defined as an instable shape and will switch to a stable one by the formation control strategy. In this way, the formation switching is just the transition among those three shapes.

The shape in Fig.6 (a), which is defined as the initial shape, can be expressed by the graph theory as

$$G1 = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix} \tag{1}$$

where 1 in the *i*-th row and *j*-th column represents an incoming edge from robot R_i to R_j, which means R_i follows R_j. In the *i*-th row, the sum of cell 1 means the number of the lead robots for robot R_i, for example in $G1$, R_3 has two leaders. Compared with the high-triangular matrix expression (Desai, *et al*, 1998), this low-triangular matrix not only describes the shape character, but also shows the lead-follow relations and robots roles in the team. Combined with the parameters stored in the VFD module, which can be seen in Fig. 5, e.g. team position, robots roles, inter-robots distance and robots orientation, the matrix $G1$ can describe a unique shape.

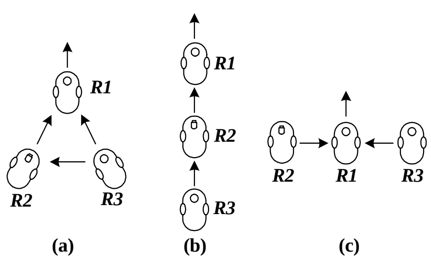

Fig. 6 Team shapes and robots positions

Considering the influence of environment, the robots team with diamond shape must change its shape into a column or line one. The analysis on these two cases is similar, so only the first case is discussed in detail. The matrix $G2$ is defined to express the terminal column shape. There are six choices for $G2$

$$G2 \in \left\{ \begin{matrix} \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \\ \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \end{matrix} \right\} \tag{2}$$

The corresponding robot sequences from leader to follower in that column shape are $R_1 - R_2 - R_3$, $R_1 - R_3 - R_2$, $R_2 - R_1 - R_3$, $R_2 - R_3 - R_1$, $R_3 - R_1 - R_2$ and $R_3 - R_2 - R_1$. Transition matrix H is defined to express the switching process from $G1$ to $G2$. $H = G1 - G2$. Corresponding to (2), there are also six choices for H

$$H \in \left\{ \begin{matrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ -1 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \\ \begin{bmatrix} 0 & 0 & 1 \\ -1 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 1 \\ -1 & -1 & 0 \end{bmatrix} \end{matrix} \right\} \tag{3}$$

where 1 in the matrix H represents the appearing of a new lead-follow relation of two robots while -1 means a disappearing of that relation. The smallest change in (3) is defined as the best choice for H. H and its corresponding $G2$ are

$$H = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \qquad G2 = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{4}$$

The terminate team shape, which can be expressed with matrix $G2$, is shown as Fig.6 (b). The team shape switching contains two steps. First one is the cancel of the lead-follow relation between R_1 and R_3, like the matrix H shows. The second step is the shape adjusting based on the team parameter, for example, the column team requires three robots moving to a straight line position with equal distance, which will be realized in 4.2.

4.2 Formation Control Strategy

The motion variable of the team is defined as $P(x(t), y(t), V(t), \omega(t))$ and the position (x, y) at time *t* is the same as $T(x, y, \theta)$ in Fig.2. Considering the matrix $G1$ and $G2$, which express the team shape, the inter-robots position and the lead-follow relation, the *i*-th robot motion variable, $R_i(x_i, y_i, V_i, \omega_i)$ can be calculated from *P*. Define $R_0(x_0, y_0, V_0, \omega_0)$ as the leader for the *t*-th robot $R_t(x_i, y_i, V_i, \omega_i)$. The control aim is to maintain a desired distance *l* and a desired relative angle φ between R_t and R_0 . The kinematics equations is given by (Chen, *et al*, 2004)

$$\begin{cases} \dot{l} = V_t \cos\gamma - d\omega_t \sin\gamma - V_0 \cos\varphi + d\omega_0 \sin\varphi \\ \dot{\varphi} = \frac{1}{l}(V_0 \sin\varphi - V_t \sin\gamma - d\omega_t \cos\gamma + d\omega_0 \cos\varphi - l\omega_0) \end{cases} \quad (5)$$

where θ_0 is the orientation of the leader robot R_0 and θ_t is that of the *t*-th robot. $\gamma = \varphi + \theta_0 - \theta_t$. Variable (l_d, φ_d) is defined as the distance and relative angle that the *t*-th robot should move. The control aim for the team formation is $(l - l_d) \to 0$ and $(\varphi - \varphi_d) \to 0$. The control strategy can be written as

$$\begin{cases} \dot{l} = \beta_1(l_d - l) \\ \dot{\varphi} = \beta_2(\varphi_d - \varphi) \end{cases} \quad (6)$$

where β_1 and β_2 are the proportional control coefficients. The control variable can be drawn from (5) and (6) as

$$\begin{cases} V_t = \rho + d\omega_t \tan\gamma \\ \omega_t = -\frac{\cos\gamma}{d}[\beta_2 l(\varphi_d - \varphi) - V_0 \sin\varphi \\ \qquad - d\omega_0 \cos\varphi + l\omega_0 + \rho \sin\gamma] \end{cases} \quad (7)$$

where $\rho = \frac{\beta_1(l_d - l) + V_0 \cos\varphi - d\omega_0 \sin\varphi}{\cos\gamma}$.

Considering the limitation of $(V_{t,\max}, \omega_{t,\max})$, the final team formation control strategy is

$$V_t = \begin{cases} V_{t,\max} & V_t > V_{t,\max} \\ V_t & -V_{t,\max} \le V_t \le V_{t,\max} \\ -V_{t,\max} & V_t < -V_{t,\max} \end{cases}$$
$$\omega_t = \begin{cases} \omega_{t,\max} & \omega_t > \omega_{t,\max} \\ \omega_t & -\omega_{t,\max} \le \omega_t \le \omega_{t,\max} \\ -\omega_{t,\max} & \omega_t < -\omega_{t,\max} \end{cases} \quad (8)$$

4.3 Individual Robots Control

Several behaviours may be motivated simultaneously during a robot executes a state. For example, the basic behaviours designed for Fortier-I include move-to-goal, circle-around-goal, avoid-region-edge, avoid-obstacle and search-objects (Jia, *et al*, 2003). Motor scheme is the best choice to fuse these behaviours (Arkin and Balch, 1997). The synthesis of the parallel behaviour vectors can be written as

$$V = \sum_{i=1}^{n} w_i V_i \ , \ \omega = \sum_{i=1}^{n} w_i \omega_i \quad (9)$$

where (V_i, ω_i) represents the isolated *i*-th behaviour forward and swerve speed. w_i represents the related weight. $\sum_{i=1}^{n} w_i = 1$. In formation, (8) express the formation-keeping and move-to-goal behaviour. The other key behaviour is obstacle avoiding, which is the basic ability of robots and has mature realization method. The control variable *V* and ω will be sent to motion controller and drive motors to realize the robots basic actions.

5. EXPERIMENT AND RESULTS

An environmental adapting formation of heterogeneous robots team is designed as the case study. It has a clear background. Suppose a pathfinder team meets with an alleyway, which is very narrow compared with the team width, just like Fig. 7 shows. The team must change its shape to pass it successfully and safely, which is shown in Fig.8.

The experiment is carried out in an open ground. Before the alleyway, blue and yellow pillars are placed as the entrance indication while at the end of the alleyway there are blue and pink pillars. *R*1 and *R*3 are Frontier-I robots, which have omni-direction cameras to find the colourful objects and calculate their position. *R*1 is the leader to find the entrance while *R*3 is a follower to find the exit.

The team-oriented task description tool is adopted to define the team trajectory. The VFD graph designed to describe the process is shown in Fig.9. Its first subtask, VFD-*A*, is a diamond shape formation. At VFD-*B* the leader finds the alleyway entrance and the team cancels the previous subtask and moves to the entrance with a column shape. The target position of the entrance is calculated as the middle position of the two detected colourful objects. VFD-*A* is a non-completed state. VFD-*C* is an assembled state that contains the shapes switching and forward motion, in which a long enough destination $T(0,80000,90^\circ)$ is set to ensure the team passing by the alleyway successfully.

The team trajectory in formation is shown in Fig.10 and the inter-robots distance is shown in Fig.11.The process *AB* in Fig.10 shows the scene of the team before the alleyway and *BC* shows the team passing it. *L*1, *L*2 and *L*3 are defined to express the distance between *R*1 and *R*2, *R*1 and *R*3, *R*2 and *R*3 respectively.

In Fig.11, the point *A* is the initial time. The team starts with 1000mm inter-robots distance. *AB* shows the team grouping process to get a diamond shape. *BC* shows team shape switching process. *L*3 in *AB* is unsmooth because *R*3 follows *R*1 and *R*2, but the lead-follow relation with *R*2 is priority. *L*1, *L*2 and *L*3 have great changes in *BC* compared with their previous value. Because in shapes switching process, *R*1 still moves forward while *R*2 and *R*3 adjust their positions. It has no influence on the team performance.

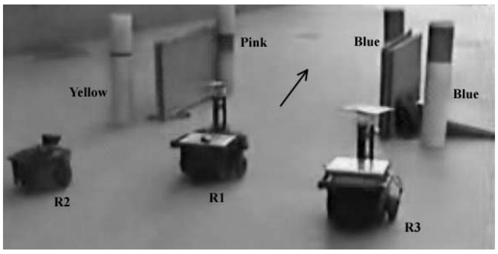

Fig. 7 Experiment system

Fig. 8 Team passing by the alleyway

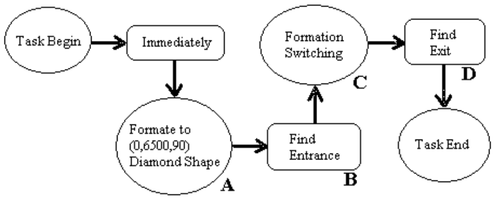

Fig. 9 VFD graph for alleyway formation.

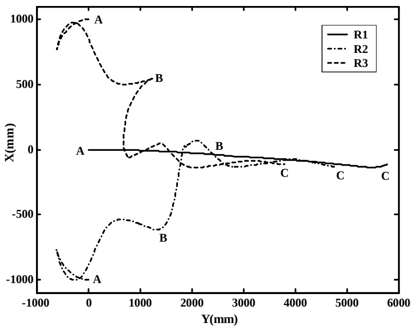

Fig.10 Team trajectory

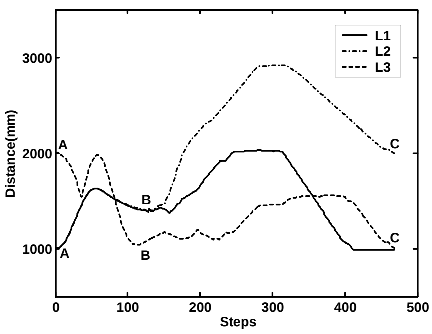

Fig.11 Inter-robots distance

6. CONCLUSION

A team-oriented formation method is presented in this paper. The first contribution of this paper is the introduction of the team-oriented concept, which has clear background in real application and generates the complex robots task conveniently. The other one is the formation switching method based on the choice of the transition matrices.

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