Formation Control of the Multi-Robot Team's Behaviors Based on Decentralized Strategies

Kuo-Yang Tu and Min-Tzung Chang Chien

Institute of system information and Control,
National Kaohsiung First University of Science and Technology
2, Juoyue Rd., Nantsu, Kaohsiung 811, Taiwan, R. O. C.
e-mail: tuky@ccms.nkfust.edu.tw

Abstract—***It is difficult for multi robots to execute team behaviors because real-time information of all robots cannot be gathered in one robot easily. In this paper, decentralized formation control laws for the team's behaviors are developed. There are three law designed for four formations, including line, column, diamond and V formations. The controller gain for better performance is examined. In addition, formation planning is proposed not only to solve a multi-robot team for complicated behaviors, but also to simplify the formation control of the complicated behaviors. Illustrative examples include the behaviors of a multi-robot team to cross over a door and avoid an obstacle. A simulator designed and developed for demonstration is also included.***

Keywords —List key index terms here. No mare than 5.

I. INTRODUCTION

It is quite interesting to study formation control for maintaining the behaviors of a multi-robot team. Due to boosting the computation power of computer, the research of this realm has obviously evolved in recent years. Peter Stone, one member of the champion team in RoboCup simulation league, designed Layered Learning in Multi-agent Systems for formation planning and task assignment [1]. This manner used complicated and centralized operation to make a very large scalar system effective.

In the study of decentralized approach, Lawton [2] proposed three control algorithms, coupled dynamics formation control with passivity-based interrobot damping and coupled dynamics approach with saturation control, and demonstrated feasible results. Lawton's manners applied to only three robots. Although its paper mentioned that this manner can be extended to a team with n robots, the team built by larger members cause bigger errors of position and velocity. As a result, the team won't finish assigned task. A team over three robots thus needs to study its feasibility.

In addition, Balch [3] considered practical calculation structure to propose various basic team formations. The proposed basic team formations designed for vehicles and omnidirectional robots are demonstrated by simulation for the study of position error and time slot deviation. This research provides the experimental data for the multi-robot team to turn movement direction for obstacle avoidance. Based on the experimental data, the team behavior control influenced by increasing or decreasing members of the robots is studied.

Stipanovic [5] separated the complex interconnected system originally formed by a multi-robot team into many simple systems to make the algorithms chosen between centralized and decentralized control possible. The large member of team robots can be divided into many small units to go through obstacles. After going through the obstacles, the team behavior can switch to original formation. Although this method has the result similar to Des [6], their implementation is real difference. Des's method has better performance on some suitable situation only, but Stipanovic's method induced many basic formations for flexibly switching in various situations. The basic formations based on environmental situation make the team behavior controlled on switching and maintaining easy to face abruptly events.

However, the authors consider that formation control of a multi-robot team is not just the path planning and motion control like traditional robot control. How to still maintain a robot formation to overcome accident events is a crucial issue of the behaviors finished by a multi-robot team for a task. In this paper, the authors propose the notion formation planning during behavior control of a multi-robot team. Time slots defined for switching formations for maintaining a behavior lead a multi-robot team to have appropriate response as meeting difficult tasks such as door cross or obstacle avoidance. Illustrative examples thus include formation control of the behaviors of crossing over a door and avoiding an obstacle. For demonstrating the formation planning, a simulator is developed for monitoring team behaviors and understanding how to adjust team behaviors' parameters. Simulation also compares the results of the formation control adjusted by distinct parameters.

II. MULTI-ROBOT TEAMS

In biology system, team behaviors are the general notion since animal basic ability such as hunting, defending, etc, is constructed under living together. For example, the birds of a team can safely fly in the formation of V, J or echelon formation without hitting each other in a behavior. Based on this phenomenon, some researchers developed on theoretical and practical study for control algorithms [3]. In addition, some researchers proposed control algorithms based on the hunting behaviors.

Therefore, it is worth to study multi-robot formation control based on biology behaviors. Balch developed the control algorithm for four vehicles applied to military. Using four vehicles as an unit, traditional method needs long time for training and complicated steps to accumulate experience, but the control algorithms based on biology behaviors make the implementation of multi-robot team behaviors easy.

Generally, the design of multi-robot teams is based on the following considerations:

1) Unit-center-referenced
2) Leader-referenced
3) Neighborhood-referenced

In addition to these considerations, some researchers combine with other needs. For instance, Das [6] proposed using neighborhood as reference in the team of two robots, and extending to that of three robots based on the two neighborhood robots. The extension method is based on grouping robots 1 and 2, grouping robot 2 and 3, etc. Under this method, a team of three robots has two groups, robots 1 and 2, and robots 2 and 3. In communication, only robot 2 spends two times for reducing the computation time of control algorithm. In structure, the system designed like a link makes maintenance and upgrade easy. On the other hand, Das's method adjusted robot's distance based on both two and three robots in groups to keep the team behaviors robustly. Based on this system structure, this method is extended to implement the team of n robots.

Lawton's manner is similar to Feddema's [4]. However, the reference robot of Feddema's manner begins at the first robot, and ends at the final robot in spite of the groups of two robots or three robots. Based on three robots in a group, Lawton's manner begins the first robot, but ends the first robot after scheduling over the final robot. The benefit of Feddema's manner reduces computation time by only needing the relationship between the neighborhood robots. Combined with the switching control strategy, Lawton's method wastes much less computation time. As a result, Lawton's method has perfect function to group up the whole team, and to provide effective control of formation behaviors.

III. BASIC FORMATIONS OF A MULTI-ROBOT TEAM

In the control of multi-robot team, there are the following formations:

(1) Line
(2) Column
(3) Diamond
(4) Wedge
(5) V shape
(6) J shape

Designating the variables of team formation is the key point of behavior control. There are many control variables such as the distance errors between present and start or final position, the angles errors between present and start or final orientation, etc, used as the variables in formation control.

In this paper, four formations and three control strategies are studied. Four formations including line, column, Diamond and reverse V shape, and three control strategies are developed to control a team of five robots on four behaviors, forward, backward, turn right and turn left. Figs. 1, 2, 3 and 4 show the four formation, respectively.

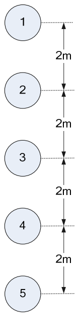

Fig. 1. Line formation.

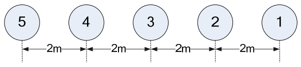

Fig. 2. Column formation.

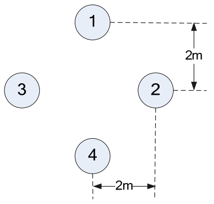

Fig. 3. Diamond formation.

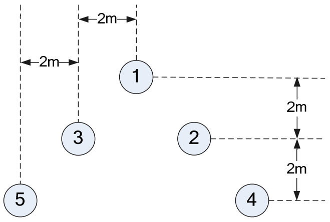

Fig. 4. The formation of reverse V shape.

The line formation as shown in Fig. 2 is a crucial behavior been able to observe the performance of a formation controller. In this formation, the controller performance can be used to predict the fault in the other team formations. The control of a team movement implies behavior stability and performance. In this study, we first focus on the control of a line formation for understanding how to design control law. For the line formation, four behaviors, forward, backward, turn left and turn right, are designated to observe and test the performance of control law and formation arrangement. The behavior control of a team formation finishes from starting at initial position to arriving at final position during movement.

IV. FORMATION PLANNING AND CONTROL

Let the internal state of the ith robot in the team be

$$\begin{bmatrix} \dot{r}_{xi} \\ \dot{r}_{yi} \\ \dot{\theta}_i \\ \dot{v}_i \\ \dot{\omega}_i \end{bmatrix} = \begin{bmatrix} v_i \cos(\theta_i) \\ v_i \sin(\theta_i) \\ \omega_i \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1/m_i & 0 \\ 0 & 1/J_i \end{bmatrix} \begin{bmatrix} F_i \\ \tau_i \end{bmatrix} \tag{1}$$

where i is the ith robot number, (r_{xi}, r_{yi}) is the robot position, θ_i is the robot orientation, v_i is the robot velocity, w_i is the robot angle velocity, m_i is the robot mass, J_i is the moment of inertial, F_i and τ_i is the force and torque added on the robot, respectively.

Let the control laws be

$$u_i = \begin{bmatrix} \frac{1}{m_i}\cos(\theta_i) & -\frac{L_i}{J_i}\sin(\theta_i) \\ \frac{1}{m_i}\sin(\theta_i) & \frac{L_i}{J_i}\cos(\theta_i) \end{bmatrix}^{-1} \times \begin{bmatrix} V_i - \begin{pmatrix} -v_i\omega_i \sin(\theta_i) - L_i\omega_i^2 \cos(\theta_i) \\ v_i\omega_i \cos(\theta_i) - L_i\omega_i^2 \sin(\theta_i) \end{pmatrix} \end{bmatrix} \tag{2}$$

with various input v_i as follows

$$\begin{aligned} v_i = & -K_g\tilde{h}_i - D_g\dot{h}_i \\ & - K_f(\tilde{h}_i - \tilde{h}_{i-1}) - D_f(\dot{h}_i - \dot{h}_{i-1}) \\ & - K_f(\tilde{h}_i - \tilde{h}_{i+1}) - D_f(\dot{h}_i - \dot{h}_{i+1}) \end{aligned} \tag{3}$$

$$\begin{aligned} \dot{\hat{x}} = & A\hat{x}_i + \tilde{h}_i \\ v_i = & -(K_g + P)\tilde{h}_i - D\dot{h}_i \\ & - K_f(\tilde{h}_i - \tilde{h}_{i-1}) - K_f(\tilde{h}_i - \tilde{h}_{i+1}) - PA\hat{x}_i \end{aligned} \tag{4}$$

$$\begin{aligned} v_i = & -K_g \tanh(k\tilde{h}_i) - D\tanh(k\dot{h}_i) \\ & - K_f \tanh(k(\tilde{h}_i - \tilde{h}_{i-1})) \\ & - K_f \tanh(k(\tilde{h}_i - \tilde{h}_{i+1})) \end{aligned} \tag{5}$$

where $\tilde{h}_i = h_i - h_i^d$ (h_i and h_i^d are present and desired position, respectively) is the position error, $\dot{\tilde{h}}_i$ is the velocity error, and K_g, K_f, D_f, D, k and P are the parameters of the control laws.

The control law of Eq. (3) uses the position and velocity of both the robot and teammates to decide controller output, linear and angle velocity. However, it is not easy to get the velocity of robot and teammates, the control laws of Eqs. (4) and (5) are thus developed for no velocity to make implementation simple. Eq. (4) replaces the velocity team with $PA\hat{x}$ in which A is a Hurwitz matrix, P is Lyapunov equation, and both satisfy A^TP+PA^T = -Q by positive matrix. Eq. (5) handles uncertainties, including robot velocity, in the saturation function.

In addition to the analysis of formation control laws, formation planning is proposed to solve a multi-robot team for finishing a behavior. There are two complicated behaviors, door cross and obstacle avoidance, studied in this paper.

In the formation of reverse V shape, the distance between two neighborhood robots is designed by having 2m. The initial orientation of the reverse V formation is same to the final orientation. In this formation, the robot of number 1 is the team leader who can finish many hard tasks in practical consideration, but for the behavior of crossing over a door, it is a big challenge to maintain such a formation.

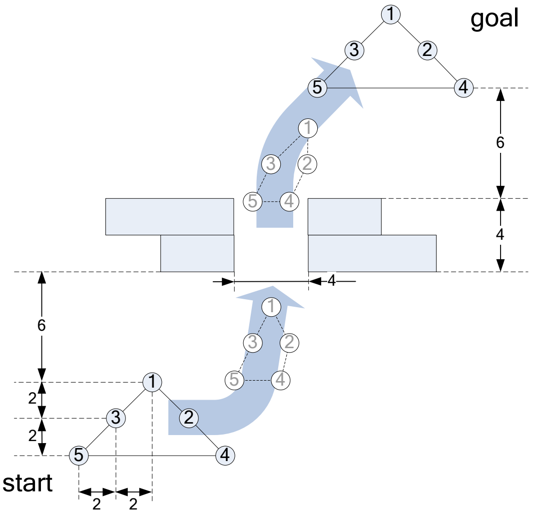

Fig. 5. The design of behavior of crossing over a door.

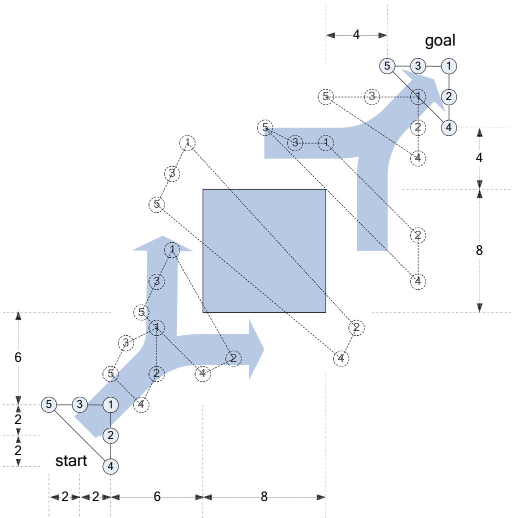

Fig. 6. The design of obstacle avoidance behavior.

The behaviors of crossing over a door is depicted as

Fig. 5. As the multi-robot team crosses over the door, its formation is deformed into a narrow reverse V shape as shown in Fig. 5 for this behavior. The time slot of deforming formation begins at the team leader (robot 1) far away from the door 6m, and ends at the last robots (robots 4 and 5) leaving the door 6m. The layout of the five robots during this time slot is shown in Fig. 5 in detail. Such a planning between formation and deformation makes the multi-robot team easy to cross over the door.

The behavior of obstacle avoidance is shown in Fig. 6. The obstacle is an 8m×8m square located at the center of this Fig. Both the initial and final formations of the team are in reverse V shape. All the distance between two neighborhood robots are 2m. For avoiding the obstacle, the multi-robot team changes formation as robot 1 far away the obstacle $6\sqrt{2}$ m. After avoiding the obstacle, the robot team changes the original formation, the reverse V shape, as the robot 5 far away from the obstacle 4m. To summarize, as meeting the obstacle, the robot team changes formation for avoiding, and after avoiding the obstacle, the robot team changes back to the original formation.

V. RESULTS

The control law of Eq. (3) can finish all the behaviors of line formation. Such result has the performance of stable movement and fast convergent speed like human behaviors during line formation. The movement of this formation can finish 24m. But, during turn right behavior, the performance of the multi-robot team becomes bad, only stable movement 10m. The control law for diamond formation also has bad performance, and gets large swinging. In addition, the backward behavior of line formation has slow convergence. From the simulation results mentioned as above, the bad performance results from large calculation for angle and velocity and the latency between the robots. After adjusting the parameters for these factors, Figs. 7 and 8 have very well performance.

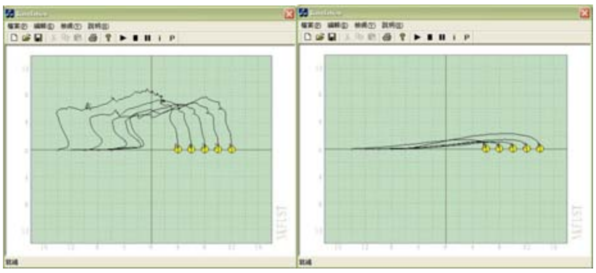

Fig. 7. The compared performance of turn right behavior in column formation by adjusting Eq. (3).

The control law of Eq. (4) has quite fast convergent speed, but stable movement in short distance. Besides, the final robot in the team occurs unstable because of calculation order. Hence, this control law can only makes the robots stable movement in shorter distance. Enlarging movement distance results in oscillating, slow convergence, and then divergence finally.

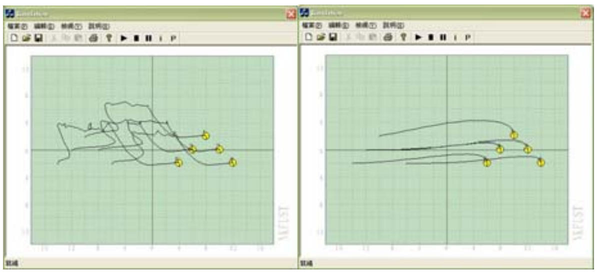

Fig. 8. The compared performance of turn right behavior in reverse V formation by adjusting Eq. (3).

By simulation experiment, data shows that the unstable phenomenon results from maintaining formation, the term K_f. K_f decides the gain for maintaining team formation. Hence, K_f is reduced for formation stability. In addition, $PA\hat{x}_i$ is also corrected because being another factor of the system in unstable.

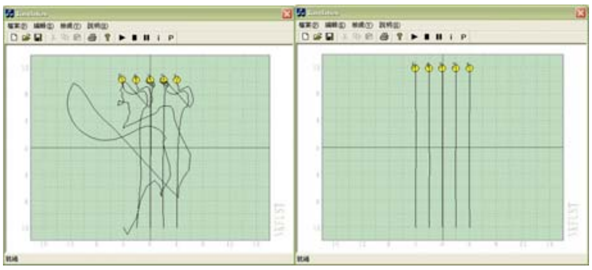

Fig. 9. The compared performance of forward behavior in column formation by adjusting Eq. (4).

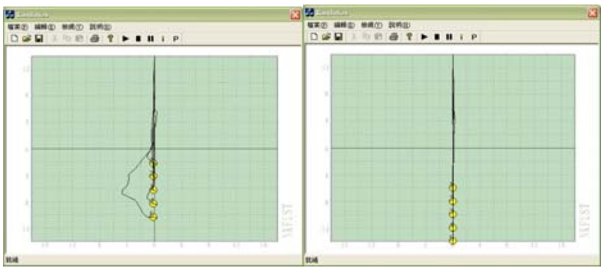

Fig. 10. The compared performance of backward behavior in column formation by adjusting Eq. (4).

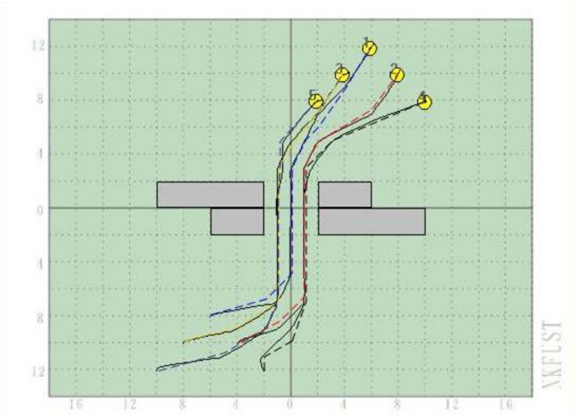

Fig. 11. The comparison of the behavior of crossing over a door in diamond formation by Eq. (5).

To summarize, the control law of Eq. (5) has the best performance. During tracking the planned trajectories, this control algorithm does not have large swinging in all formation behaviors. The robots only have large orientation movement in the backward behavior of line formation, but finish the other formation very well. Hence, it is possible for the formation control of practical two-wheel mobile robots. In addition, K_f is adjusted to get the best performance. Figs. 11 and 12 show that the control algorithm finishes the behaviors of crossing over a door and avoiding the obstacle, respectively, very well.

To summarize, Eq. (3) needs the robots' velocity to control team formation. It is not practical to implement for formation control. Besides, the huge computation time makes the finish of formation control difficult. It is practical to replaces velocity with state observer as Eq. (4). However, huge computation time is a very heave loading to implement the state observer for formation control. It is difficult to implement for the huge members of a multi-robot team. In addition, the state observer results in the deviation of robot state as inappropriate design. This is the state observer makes that the robot position cannot be controlled accurately. Eq. (5) is the best way of formation control, but its convergent speed is the slowest.

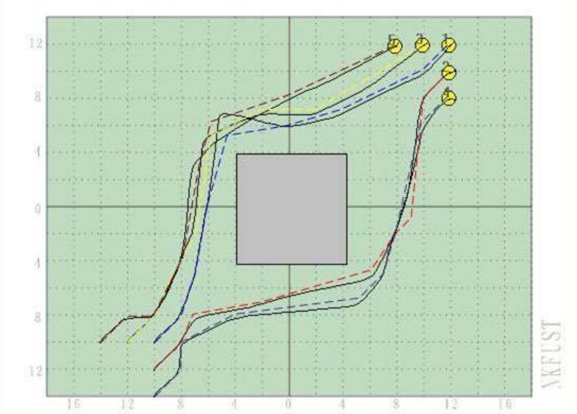

Fig 12. The compared performance of obstacle avoidance behavior in the diamond formation by Eq. (5).

VI. CONCLUSION

In this paper, the multi-robot team and formation control are analyzed to develop a simulator for studying. By basic formations and complicated behaviors, the formation control laws are studied in the developed simulator for proposing the notion of formation planning. The formation planning is demonstrated by two complicated behaviors, door cross and obstacle avoidance. The demonstration shows that for a multi-robot team, formation control needs not only path planning and motion control like traditional robot control, but also formation planning to maintain stability for solve special events.

In all of the formation control laws, K_g and D_g are the most important factors. Regardless of maintaining team formation, theses two parameters decide the trajectory following from start to end position. Four formations can be achieved by adjusting these two parameters. However, too large formation distance will make the system in unstable. In addition, increasing robot number in a team will make swinging serious, but can be solved by decreasing movement velocity. In all, it is too many factors to adjust the performance of formation control of multi-robot teams. How to adjust such many factors for the best performance is the further development.

ACKNOWLEDGMENT

This research was supported by National Science Council, Taiwan, Rep. of China under grant NSC 94-2213-E-327-014-

REFERENCES

[1] Peter Stone,1998,Layered Learning in Multiagent Systems: A Winning Approach to Robotic Soccer, MIT Press, Cambr- idge, Massachusetts, London, England.

[2] Lawton R. T. Lawton, Randal W. Beard, 2003, "A Decentralized Approach to Formation Maneuvers", IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, vol.19, NO.6, DECEMBER.

[3] Tucker Balch, Ronald C. Arkin, 1998, "Behavior-Based Formaion Control for Multirobot Teams", IEEE TRANSA- CTIONS ON ROBOTICS AND AUTOMATION, vol.14, NO.6, DECEMBER.

[4] Feddema T. Feddema, Chris Lewis, David A. Schoenwald, 2002, "Decentralized Control of Cooperative Robotic Vehi- cles : Theory and Application", IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, vol.18, NO.5, OCTOBER.

[5] Dusan M. Stipanovic, Gokhan Inalhan, Rodney Teo, Claire J. Tomlin, 2004, "Decentralized overlapping control of a formation of unmanned aerial vehicles", Automatica, Vol. 40, No. 8, pp. 1285-1296, Aug.

[6] Aveek K. Das, Rafael Fierro, Vijay Kumar, et ail. 2002, "A Vision-Based Formation Control Framework", IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, vol.18, NO.5, OCTOBER.