Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

MULTI-ROBOT TRACKING OF MOBILE TARGET BASED ON COMMUNICATION

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Abstract: Multi-robot tracking of mobile target is studied in the paper, which is based on the communication and sensors. For an independent tracking robot, the processes are separated into three layers and four tasks, and allocated to different robots for distinct roles in tracking, which is named the Distributed Decision Control System (DDCS). After that, two tracking models, centralized and distributed models, are designed for multi-robot tracking. Furthermore, a Proportional Navigation Guidance Law (PNGL) and *l*-*φ* formation control algorithm are mentioned to realize the robot motion control. At last the simulation has shown the feasibility and validity of both models.

Keyword: Multi-robot tracking, DDCS, PNGL, Communication based, *l*-*φ* formation control algorithm

1 INTRODUCTION

Robotics collaboration has shown important developments during the last decade. Multi-robot systems are used for various applications to accomplish tasks that are difficult or time consuming for a single-robot. On the other hand, in comparison to single-robot solutions, multi-robot systems are used in many situations in order to improve the flocking performance, multi-sensing ability and reliability. Problems of tracking a moving target using mobile robots were considered by many researchers, which are basic techniques of robot hunting, exploration and surveillance. Recently, multi-robot systems are introduced to accomplish the same task. Different from the single robot tracking, the specific tracking formation of robots will be kept well by the planner is a key point to achieve a good overall performance in multi-robot, exploration, surveillance, search and rescue (Arai *et al.*, 2002; Fox *et al.*, 2000; Feddema *et al.*, 2002; Jennings *et al.*,1997).

Different aspects of this special tracking problem are widely considered (Reynolds, 1987; Vicsek *et al.*, 1995; Shimoyama *et al.*, 1996; Olfati-Saber, 2006). Multi-robot tracking of a moving object using directional sensors was proposed in (Jr. *et al.*, 2004), and a sensor fusion scheme based on inter-robot communication is proposed to obtain accurate real-time information of the target's position and motion.

2 STATEMENT OF THE PROBLEM

Consider the robots, both the tracking and the target robot, moving in a horizontal plane according the following kinematics equations for nonholonomic robot:

$$dx_i / dt = V_i \cos\theta_i \qquad （2\text{-}1）$$

$$dy_i / dt = V_i \sin\theta_i \qquad （2\text{-}2）$$

$$\omega_i = d\theta_i / dt \qquad （2\text{-}3）$$

where (x_i, y_i, θ_i) denote the pose of robot i in the Cartesian frame of reference. (V_i, ω_i) show the linear velocity and angle velocity of the robot. With the different i, the robot can be the target, leader or follower.

The aim of the paper is to design a DDCS (Distributed Decision Control System), using a behavior-based control algorithm, for the multi-robot tracking a mobile target with a steady formation, and to research the fault tolerance of the track flocking by dealing with the leader broken problem easily using the NNR (Nearest Neighbor Rule) to allocate the leader task to the appropriate robot.

For the target robot R_{target}, it can perform three types of motion as (Belkhouche *et al.*, 2005):

i). Non-accelerating motion: The target robot moves with a constant orientation angle and speed.

ii). Accelerating motion: The orientation angle of the target robot is time-varying.

iii). Smart motion: The orientation angle of the target robot is time-varying but in a smart way in order to escape to the predators.

For the tracking robots, follow assumptions are given:

i). Each robot has a sensory system which allows to detecting obstacles and estimating the position of the target with respect to the robot.

ii). The robots' velocities satisfy: $V_{\text{track\_max}} > V_{\text{target\_max}}$.

iii). The robots and the target move with constant speed.

iv). The path traveled by the target robot is continuous.

3 DISTRIBUTED DECISION CONTROL SYSTEM

Communication based Mobile-target tracking by multi-robot is a typical multi-task control system. The centralized control method cannot satisfy the formation keeping, obstacles avoidance and tracking synchronously. So, a Distributed Decision Control System is utilized in the paper, which has distribution, communication and stability to the centralized control method.

3.1 Task allocating

In different stage of target tracking, trackers act disparate roles and have distinct motion tasks. At the beginning, when the target is missing from the field of tracker's view, everyone needs to play as the same role to search the target. After finding the target, which has special character as color or shape, the tracking team should join together and form the tracking formation soon. However, the tracking formation won't always static, and the original leader might change by the time varying state of the target. The tracking robots need to choose another leader and reform a new flocking automatically, to maintain the stability of the tracking formation.

We can first separate the multi-robot tracking task into four parts:

i). Searching Task: Searching the target robot in the state of "Robots Wander".
ii). Converging Task: Converging the tracking robots and appoint the Leader robot after discovery the target.
iii). Flocking Task: Form the certain formation in the tracking way.
iv). Leader Exchange Task: Exchanging the Leader robot if the situation need (by NNR).

Beside these four parts of the task, some other affiliated task as obstacle and collision avoidance task is also importance to our tracking, which can be included in the Flocking Task.

The framework of these tasks in the tracking process is shown in figure 1.

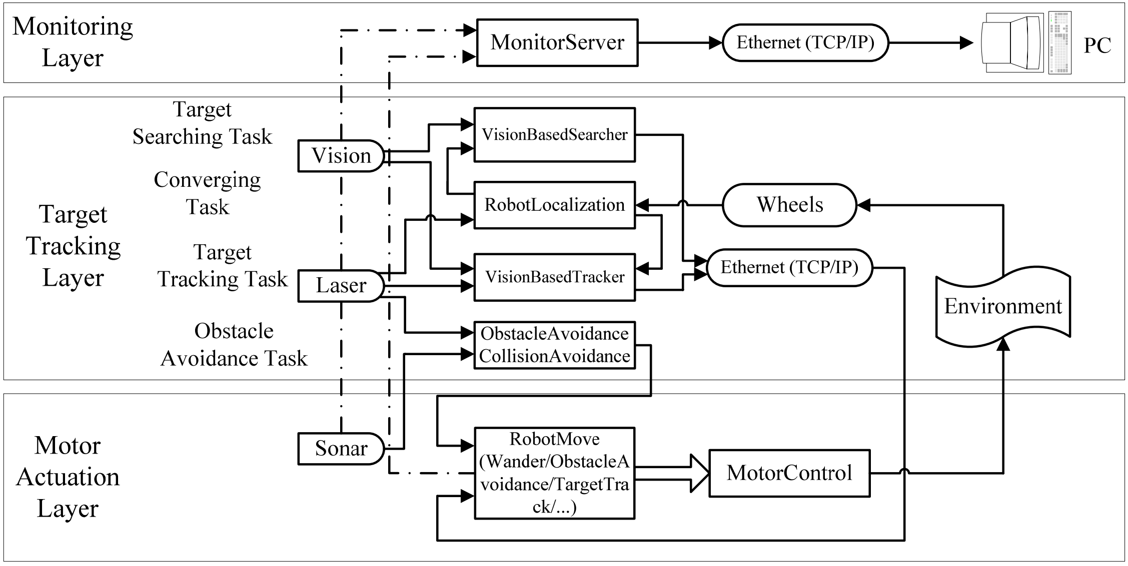


Fig. 1 The framework of multi-robot tracking process

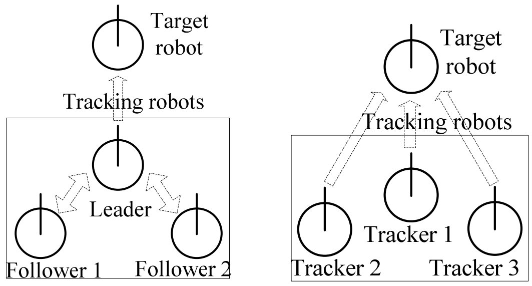
3.2 Searching and Tracking Navigation Model

The Searching and Tracking Navigation Model contain the main process of the multi-robot tracking research, which is the most important model in the problem. A relative distance between the target and tracker (viewer) by the monocular vision and laser sensor can be got in (Liu *et al.*, 2006), which is one of the basic parameters in the searching and tracking task.

In tracking navigation problem of multi-robot, the allocation of two tasks, tracking and keeping formation, should be both effective and intertwined with each other. Two general ways to solve this problem will be given here:

I) Centralized tracking model, which uses Leader-Follower formation model;
II) Distributed tracking model, which solve the formation problem in the tracking task (as in figure 2).

Thus, the Leader in (I) and the Tracker N (N=1, 2, 3…) in (II) are both assigned tracking task, with the difference that Leader in (I) need to send its position to the Follower only rather than the relative position. However, we could find a common tracking law for the trackers as Leader and Tracker N.



(I) Centralized Model (II) Distributed Model

Fig. 2 Multi-robot Tracking models

A pursuit navigation algorithm was proposed in (Belkhouche *et al.*, 2005). Three guidance laws, velocity pursuit, deviated pursuit and proportional navigation, were proposed to solve different tracking task and present different relative position of prey and tracker. Assume that all robots were modeled as wheeled mobile robot of the nonholonomic type. The robot is denoted as R_i for i=0,1,…,N-1. The relationship of any two Robots R_i and R_{i+1}, which can even be the target robot, can represent the whole robot formation. Suppose that R_{i+1} tracks R_i. The relative position of them in Cartesian is shown in figure 3.

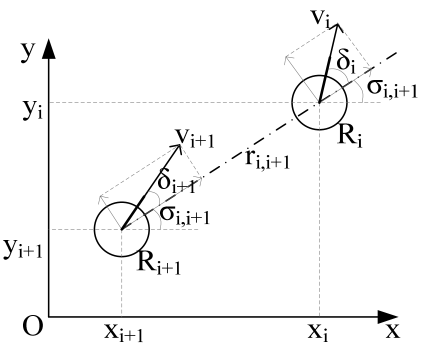


Fig. 3 The relative position of seriate robots

The relative range between them is denoted by $r_{i,i+1}=r_i-r_{i+1}$ with the obliquity of $\sigma_{i,i+1}$. The linear velocities are $v_i = \dot{r}_i$ and $v_{i+1} = \dot{r}_{i+1}$. For each pair of robots joined by the line of sight $r_{i,i+1}$, the angles are, respectively, expressed as:

$$\delta_i = \theta_i - \sigma_{i,i+1} \tag{1}$$

$$\delta_{i+1} = \theta_{i+1} - \sigma_{i,i+1} \tag{2}$$

in which θ_i and θ_{i+1} is the orientation angle with respect to the positive x-axis.

Above three guidance laws were based on the geometry and kinematics equations. The principle of the velocity pursuit is to make the velocity vector v_{i+1} of the pursuer R_{i+1} lying on the line of sight $r_{i,j+1}$. For the deviated pursuit, there exists a nonzero angle δ_{i+1} between the line of sight and the velocity vector. The proportional navigation can be seen as a generalization of the pursuit. For the proportional navigation, the angular velocity of R_{i+1} is proportional to the rate K ($1<K\leq 1+\eta$) of turn of the line of sight angle, where η is a small real number with $\eta_{max}=0.1$ describing how much the proportional navigation will be deviated from the velocity pursuit.

As mentioned previously, in our multi-robot tracking task, there're two models to solve the problem of coordination of tracking and keeping formation. In centralized tracking model, the velocity pursuit method adapts to the Leader robot with $\delta_{\text{Leader}}=0$. In distributed tracking model, different trackers request variable factors, δ_{Tracker} and $r_{i,j+1}$, to carry out two tasks simultaneity. So we prefer to use a generalization way, the Proportional Navigation Guidance Law, to conform two tracking model as possible, which is also easier to program design by computer. However, the Proportional Navigation method, proposed by Belkhouche *et al.*, 2004, was not always perfection. It dealt with the situation $\theta_{i+1}>\sigma_{i,i+1}$ only. So an intact Guidance Law will be proposed as follow.

3.3 The Proportional Navigation Guidance Law

As shown in Figure 3 before, we can decompose the velocity of R_i and R_{i+1} and express the radial velocity and the tangential velocity of the couple system as:

$$v_{(i,i+1)R} = \dot{r}_{i,i+1} = v_i \cos\delta_i - v_{i+1}\cos\delta_{i+1} \tag{3}$$

$$v_{(i,i+1)T} = r_{i,i+1}\dot{\sigma}_{i,i+1} = v_i \sin\delta_i - v_{i+1}\sin\delta_{i+1} \tag{4}$$

From the relationship of $\theta_{(i,i+1)}$ and $\sigma_{i,i+1}$ in equation (1) (2), the proportional navigation system can be defined as follow, for the purpose of robotic convoy.

$$\theta_{i+1} = K\sigma_{i,i+1} \quad (1-\eta < K \leq 1+\eta) \tag{5}$$

By taking the derivative in (5), we get:

$$\omega_{i+1} = K\dot{\sigma}_{i,i+1} \tag{6}$$

Which means that the angular velocity of R_{i+1} is equal to the rate of turn of the line of sight angle between robot R_{i+1} and R_i. The values of the radial and tangential velocity components under the Proportional Navigation Law can be written as:

$$\dot{r}_{i,i+1} = v_i\cos(\delta_i) - v_{i+1}\cos(M\sigma_{i,i+1}) \tag{7}$$

$$r_{i,i+1}\dot{\sigma}_{i,i+1} = v_i\sin\delta_i - v_{i+1}\sin(M\sigma_{i,i+1}) \tag{8}$$

$$M=K-1 \tag{9}$$

That is to say $M\in(-\eta,+\eta)$. While $\eta\in(-0.1,0.1)$, the angle $\delta_{i+1}=M\cdot\sigma_{i,i+1}\in(-\pi/2, \pi/2)$. Otherwise, it becomes an escaping situation instead of tracking. For robotic convoy, the aim of the following robots is to track the same trajectory as the lead robot. Under normal circumstance, to get an optimized trajectory, the angle δ_{i+1} won't be adjacent to $\pm\pi/2$. It is worth nothing that the coefficient M can be used in some situations for path correction and different M will give distinct tracking results, as we will see in the simulation.

So the kinematics equations for the motion of robot R_{i+1} under the Proportional Navigation Guidance Law are:

$$\dot{x}_{i+1} = v_{i+1}\cos(K\sigma_{i,i+1}) \tag{10}$$

$$\dot{y}_{i+2} = v_{i+1}\sin(K\sigma_{i,i+1}) \tag{11}$$

$$\dot{\theta}_{i+1} = \omega_{i+1} = K\dot{\sigma}_{i,i+1} \tag{12}$$

When K=1, the case corresponds to the situation that tracker is heading to the target.

When K=1+M, the case corresponds to the situation that tracker's head deviate from the sight line with the target with the angle $M\cdot\sigma_{i,i+1}$.

In robotic dynamic tracking research, there are two general stages between the trackers and target: chase and maintenance. Tracking robots will display different state with different distance to target robot. To realize stable tracking, trackers and target should be maintain relative static when the relative distance is short. In other words, the problem how to achieve a constant distance $\|r_{i,i+1}\|$ between robots is worth to research.

When $\|r_{i,i+1}\|$ becomes a constant distance, the radio velocity of the couple robots $v_{(i,i+1)R}$=0. From equation (7), we have:

$$v_{i+1} = v_i\frac{\cos(\theta_i - \sigma_{i,i+1})}{\cos(M\sigma_{i,i+1})} \tag{13}$$

With $-0.1\leq M\leq 0.1$. The Guidance Law can be proved convergent in certain situations.

3.4 Communication-based Formation

As we mentioned before, when the centralized tracking model was used in Multi-robot tracking task, the Leader needs to track the target robot and the Follower should follow the Leader with a certain formation. The traditional used stable flocking method of mobile robots under the Leader-Follower System is model-based Flocking Method. However, the model of multi-robot is always complex. Thus, the common way is to use multi-agent model as substitute, in which the abilities of apperceiving and communication are necessary. In this section, we use a communication-based formation method to solve the flocking problem.

In the real time controlling environment, the external sensors such as laser equipments are always shielded by the obstacles, so the neighbor robots coordination can be achieved through communication channel only. Therefore the internal sensors such as the encoders are utilized to achieve the local robot position. And the external sensors are utilized to obstacle and collision avoidance. Both sensors information can be sent to neighbor robots by communication.

The framework diagram of the multi-robot flocking is shown in figure 4.

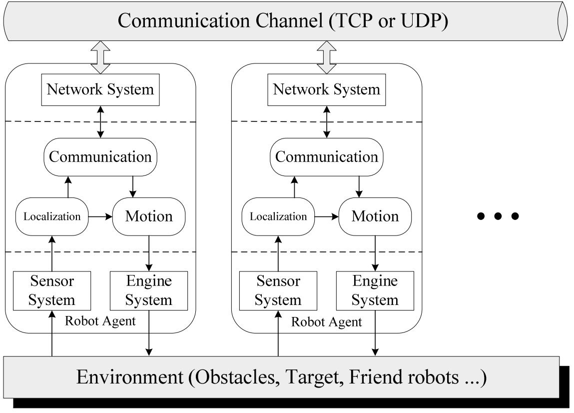


Fig. 4 The framework of multi-robot flocking

In figure 5, we show the motion control framework diagram for a single robot, which shows the program flow likewise.

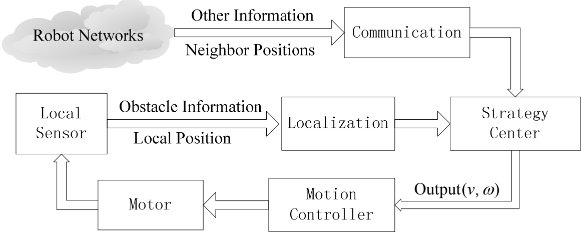


Fig. 5 The framework of robot in flocking

To demonstrate the validity of such design, multi-robot closed-loop l-φ formation control algorithm (shown in Figure 6) is adopted. Desai *et al.* have described two scenarios for feedback control within a formation. One is l-φ algorithm, and the other one is l-l algorithm. In the first scenario, one robot follows another by controlling the relative distance and orientation between the two. This situation is applicable to all formations in which each robot has one leader except for the lead robot.

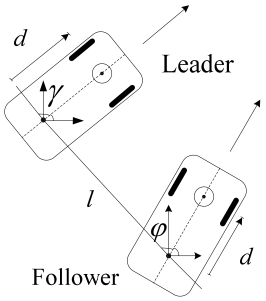


Fig. 6 The l-φ formation control algorithm

3.5 Leader selection and exchange rules

In the centralized tracking model, the leader robot has act the essential role in flocking, which should influence all the followers in tracking model. Otherwise, the fault tolerant ability is also important for multi-robot tracking. How to exchange the damaged or useless Leaders should be considered also. Here a rule for leader selection and exchange is designed.

The rule of leader choosing and the flocking operation of a team of mobile robots are as follows:

i). Avoid obstacle using safeguard behavior with highest priority, based on sonar data;
ii). Become a leader if it is in a good position and no other robots are visible, and wander around;
iii). Try to maintain its position if it is in a flock;
iv). Speed up and head towards a flock which can be seen in the distance.

While the robots are created in the environment, the rule of leader selection will be effective simultaneously. With which, the flocking system will confirm the leader robot every time lag.

4 SIMULATION AND RESULTS

The "MuRoS Multi-Robot Simulator" (Chaimowicz *et al*., 2002) is used in our simulation, which is open source. In the MuRoS Simulator, the robot is simplified as the small gray wafers with a short line to denote its direction (in figure 7 and 9).

4.1 Centralized tracking model

As in figure 7, there are three sub-figures express the process from the initial to stable tracking respectively. The leftmost one is the target object for tracking. Other five wafers denote the trackers. The first sub-figure is the initial state of the robots and the last one is the stable formation. In the formation, the robot 0 is the leader of flocking, which is selected by the rule in 3.4.

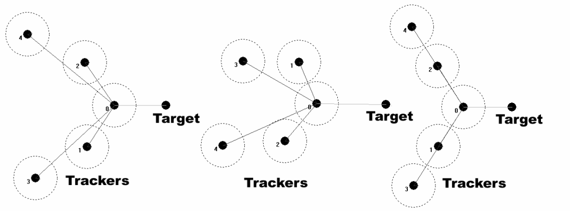


Fig. 7 The centralized tracking formation

The position and velocity curves of the tracking robots in flocking are shown in figure 8. The Robots from No. 0 to No. 4 are the trackers in figure 7.

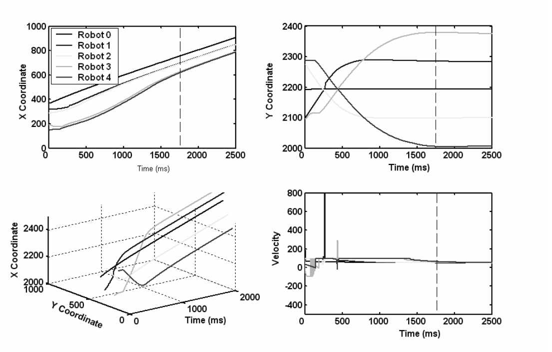


Fig. 8 The position and velocity curves of robots in centralized model

From the curves we can find that the position and velocity will keep a certain value after about 1.6s in simulation. It means that the tracking formation reaches a stable state then. The tracking is successful in the centralized model.

4.2 Distributed tracking model

The figure 9 and 10 have shown the stable tracking formation and the position/velocity curves of trackers in the distributed tracking model. The trackers are all related to the target robot directly. The sequence of the tracking robots is decided by the initial position of them.

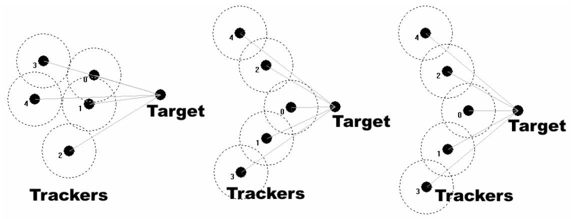


Fig. 9 The distributed tracking formation

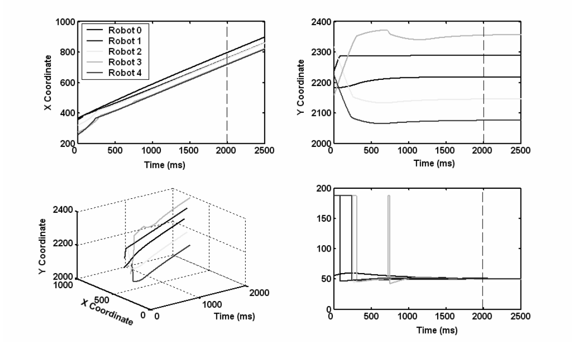


Fig. 10 The position and velocity curves of robots in distributed model

From the curves we find that the formation reaches stable state in about 2s.

5 CONCLUSION

The paper has researched multi-robot tracking of the mobile target, which is a class of flocking theory. The communication is the basic relationship between the seriate robots and the sensors are used to detect the target and obstacles. For each robot, if it's in the distributed model or is the leader of centralized model, its tracking processes are separated into three layers: monitoring layer, target tracking layer and motor actuation layer, and the tracking layer contains four tasks: searching task, converging task, flocking task and leader exchange task. Otherwise, its only task is to follow the leader. After that, two tracking models, centralized and distributed models, are used for multi-robot tracking.

Furthermore, a Proportional Navigation Guidance Law which can be proved a in certain situations, is mentioned to realize the robot motion control. And Desai's l-φ formation control algorithm is also used for the following control between the leader-follow systems.

At last the simulation has shown the feasibility and validity of the both models.

ACKNOWLEDGMENTS

This work is supported in part by National Natural Science Foundation of China under the grant 60674105 and NSFC International Collaborative Project under the grant 60340420431.

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