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Multi-Robot Cooperative Hunting

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Abstract— **This paper presents a Lyapunov based cooperative hunting method for multiple robots. First, the relative dynamics is obtained from the robot-target relative kinematics. Then, using the relative dynamics and dynamics of all the robots, a Lyapunov based local controller is derived to stabilize individual robots. Afterward, the cooperative control law is obtained by adding an extra term to the local controller, which represents the mutual difference in tracking errors. The closed-loop system is proved to be asymptotically stable using Lyapunov Stabilization Theorem. Further, the performance of the cooperative hunting method using a group of non-holonomic robots is evaluated using simulation. The results show that the robot group can effectively track and trap the target simultaneously.**

Keywords- cooperative hunting, Cooperative control, multiple robots, formation control, and Lyapunov stability.

I. INTRODUCTION

Using multiple robots for cooperative missions has received extensive attention during the past decades due to its potential to complete complex tasks more efficiently [1]. Some of the extensively studied tasks involving multiple robots are formation following [2-5], multi-robot tracking [6, 7], surveillance [8], exploration [9], search and rescue [10], and hunting [11].

Most of the multi-robot cooperative hunting systems are implemented as strategies to pursue and encircle the targets, such as the following [11-13]. Yamaguchi et al. studied a distributed control scheme for multiple robotic vehicles to make group formations using locally measured relative position and orientation information [11, 14]. The dynamics of a robot vehicle was formulated as a first order linear model in consideration of its relative position to others. Based on that, a stabilizing control vector was derived. Further, Nighot et al. studied multi-robot coordination strategy to capture targets using particle swarm optimization method [12]. While, Belkhouche et al. separated the cooperative hunting behavior into four different modes, i.e., navigation-tracking mode, obstacles avoidance mode, cooperative collision avoidance mode, and circle formation mode. Then, different strategies were applied to achieve the intermediate goal [13]. Multi-robot hunting in unknown environments using local interactions with local coordinate systems were studied [15]. In this study, the hunting task is divided into four states, i.e., search, pursue, catch, and predict states. In [16], the cooperative hunting for multiple mobile targets by multi-robot was studied, where the hunting process was divided into group formation and capturing stages. Cooperative hunting using a limit-cycle based algorithm was studied in [17], where the formation is obtained using artificial potential field and the limit-cycle based algorithm was utilized to encircle the target. In [18], the cooperative hunting was also divided into pursuit and capture modes. Pursuit was implemented using neural network based control and capture could use dynamic alliance and formation construction algorithms. Game theory was also explored for multi-robot hunting [19]. A coordinated hunting model is derived from the extended cooperation game.

Most of these existing cooperative hunting methods focus on selecting or developing different strategies/methods for different stages of hunting. In this paper, cooperative hunting using a group of nonholonomic car-like robots is studied. The rest of the paper is organized as follows. In Section II, the problem formulation is presented. The relative dynamics is derived in Section III; Section IV talks about the cooperative hunting control design. Section V presents the simulation results. Finally, conclusions are given in Section VI.

I. PROBLEM FORMULATION

To describe the absolute and relative motion relationship, the global coordinate $(X_0 - Y_0)$ and local body coordinates of the robot agents $(X_i - Y_i)$ are defined as shown in Figure 1.

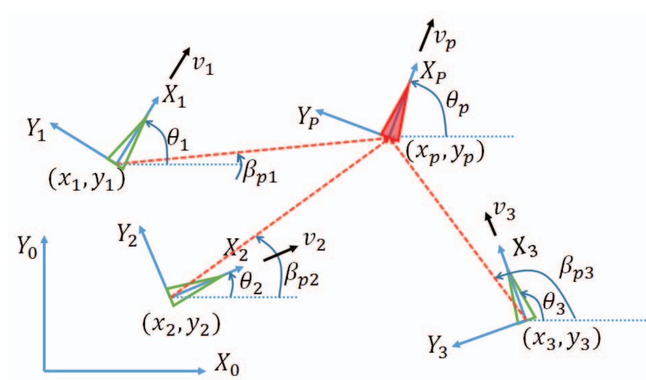

Figure 1. Definition of coordinate and relative configuration

Here, the origins of a robot agent i is given as (x_i, y_i), heading angle θ_i is defined as the angle between X_0 and X_i, the angle of sight β_{pi} is defined as the angle between X_0 and the relative position vector $\boldsymbol{r}_{pi}$ of the prey with respect to the hunting robot i, and the velocity of robot is v_i.

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The goal of cooperative hunting is to encircle the prey (target) as soon as it has been detected. The desired relative positions of the hunting robots and target are shown in Figure 2. The mathematical description of the desired state is

$$\begin{cases} \begin{Bmatrix} x_p \\ y_p \end{Bmatrix} - \begin{Bmatrix} x_i \\ y_i \end{Bmatrix} = r_0 \angle \varphi_i \\ \varphi_{i+1} - \varphi_i = \frac{2\pi}{n} \end{cases}, as\ t \to \infty. \tag{1}$$

where n is the number of robots in the hunting group, and r_0 is the radius of the desired circle.

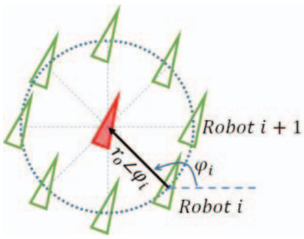


Figure 2. Desired state of cooperative hunting

II. Relative Dynamics

To define the relative positon of the target with respect to individual robot,

$$\boldsymbol{r}_{pi} = \begin{Bmatrix} x_p \\ y_p \end{Bmatrix} - \begin{Bmatrix} x_i \\ y_i \end{Bmatrix}. \tag{2}$$

The relative velocity relationship between the prey (target) and predator (robots) can be described using the following kinematics equation.

$$\begin{cases} \dot{r}_{pi} = v_p\, cos(\theta_p - \beta_{pi}) - v_i\, cos(\theta_i - \beta_{pi}) \\ r_{pi}\dot{\beta}_{pi} = v_p\, sin(\theta_p - \beta_{pi}) - v_i\, sin(\theta_i - \beta_{pi}) \end{cases} \tag{3}$$

where v_p and v_i are the speed of the prey p and predator i, respectively.

Considering the prey and predators move in horizontal plane, their kinematics are as follows,

$$\begin{cases} \dot{x}_p = v_p\, cos(\theta_p) \\ \dot{y}_p = v_p\, sin(\theta_p) \end{cases} \tag{4}$$

and

$$\begin{cases} \dot{x}_i = v_i\, cos(\theta_i) \\ \dot{y}_i = v_i\, sin(\theta_i) \end{cases} \tag{5}$$

The dynamics can be modeled as

$$\begin{cases} \begin{Bmatrix} \dot{x}_p \\ \dot{y}_p \end{Bmatrix} = \begin{Bmatrix} v_p\, cos(\theta_p) \\ v_p\, sin(\theta_p) \end{Bmatrix} \\ \begin{Bmatrix} \dot{v}_p \\ \dot{\theta}_p \end{Bmatrix} = \boldsymbol{u}_p \end{cases} \tag{6}$$

where the control $\boldsymbol{u}_p = \begin{Bmatrix} a_p \\ \omega_p \end{Bmatrix}$. The terms $a_p = \frac{F_p}{m_p}$ and ω_p are the acceleration and angular velocity. F_p and m_p are the traction force and mass of the prey. Similarly, the dynamics equation of motion for the predator i is

$$\begin{cases} \begin{Bmatrix} \dot{x}_i \\ \dot{y}_i \end{Bmatrix} = \begin{Bmatrix} v_i\, cos(\theta_i) \\ v_i\, sin(\theta_i) \end{Bmatrix} \\ \begin{Bmatrix} \dot{v}_i \\ \dot{\theta}_i \end{Bmatrix} = \boldsymbol{u}_i \end{cases} \tag{7}$$

where the control $\boldsymbol{u}_i = \begin{Bmatrix} a_i \\ \omega_i \end{Bmatrix}$, $a_i = \frac{F_i}{m_i}$ is the acceleration, ω_i is the angular velocity, and F_i and m_i are the traction force and mass of the prey.

Take the time derivative of the relative kinematics in Eq.(3) , we can get

$$\begin{aligned} \ddot{r}_{pi} = r_{pi}\dot{\beta}_{pi}^2 + \dot{v}_p \cos(\theta_p - \beta_{pi}) - v_p \sin(\theta_p - \beta_{pi})\,\dot{\theta}_p \\ -\dot{v}_i \cos(\theta_i - \beta_{pi}) + v_i \sin(\theta_i - \beta_{pi})\,\dot{\theta}_i \end{aligned} \tag{8}$$

$$\begin{aligned} \ddot{\beta}_{pi} = -\frac{2}{r_{pi}}\dot{r}_{pi}\dot{\beta}_{pi} \\ +\frac{1}{r_{pi}}\begin{Bmatrix} \dot{v}_p \sin(\theta_p - \beta_{pi}) - \dot{v}_i \sin(\theta_i - \beta_{pi}) \\ +v_p\dot{\theta}_p \cos(\theta_p - \beta_{pi}) - v_i\dot{\theta}_i \cos(\theta_i - \beta_{pi}) \end{Bmatrix} \end{aligned} \tag{9}$$

Since $\dot{v}_p$ and $\dot{\theta}_p$ are the maneuvers that the prey took to escape, it is generally unknown and to be estimated through an estimator design. Here, for the demonstration purpose of using this method for the cooperative hunting, it is assume that $\dot{v}_p = 0$ and $\dot{\theta}_p = 0$. The hunting performance can be further improved by designing an estimator for these two variables. With this assumption, the dynamics in (8) and (9) can be simplified as

$$\ddot{r}_{pi} = r_{pi}\dot{\beta}_{pi}^2 - \dot{v}_i \cos(\theta_i - \beta_{pi}) + v_i \sin(\theta_i - \beta_{pi})\,\dot{\theta}_i \tag{10}$$

$$\ddot{\beta}_{pi} = -\frac{1}{r_{pi}}\{2\dot{r}_{pi}\dot{\beta}_{pi} + \dot{v}_i \sin(\theta_i - \beta_{pi}) + v_i\dot{\theta}_i \cos(\theta_i - \beta_{pi})\} \tag{11}$$

To simplify the relative dynamics in Eq. and, let us define

$$\boldsymbol{f}_i = \begin{Bmatrix} r_{pi}\dot{\beta}_{pi}^2 \\ -\frac{2}{r_{pi}}\dot{r}_{pi}\dot{\beta}_{pi} \end{Bmatrix}, \text{ and} \tag{12}$$

$$B_i = \begin{bmatrix} -cos(\theta_i - \beta_{pi}) & v_i\, sin(\theta_i - \beta_{pi}) \\ -\frac{1}{r_{pi}} sin(\theta_i - \beta_{pi}) & -\frac{1}{r_{pi}} v_i\, cos(\theta_i - \beta_{pi}) \end{bmatrix}, \tag{13}$$

then, the relative dynamics can be written as

$$\begin{Bmatrix} \ddot{r}_{pi} \\ \ddot{\beta}_{pi} \end{Bmatrix} = \boldsymbol{f}_i + B_i u_i \tag{14}$$

where the control $\boldsymbol{u}_i = \begin{Bmatrix} \dot{v}_i \\ \omega_i \end{Bmatrix}$.

III. Control System Design

A. Individual Control Law

$$\text{Let } \boldsymbol{x}_{i1} = \begin{Bmatrix} r_{pi} \\ \beta_{pi} \end{Bmatrix}\ and\ \boldsymbol{x}_{i2} = \begin{Bmatrix} \dot{r}_{pi} \\ \dot{\beta}_{pi} \end{Bmatrix}, \tag{15}$$

Eq. (14) can be written as

$$\begin{cases} \dot{\boldsymbol{x}}_{i1} = \boldsymbol{x}_{i2} \\ \dot{\boldsymbol{x}}_{i2} = \boldsymbol{f}_i + B_i \boldsymbol{u}_i \end{cases} \tag{16}$$

Let $\boldsymbol{e}_{i1} = \boldsymbol{x}_{i1} - \boldsymbol{x}_{i1}^{des}$ *and* $\boldsymbol{e}_{i2} = \dot{\boldsymbol{x}}_{i1} - \dot{\boldsymbol{x}}_{i1}^{des}$, (17)

since $\boldsymbol{x}_{i1}^{des}$ is a constant, $\dot{\boldsymbol{x}}_{i1}^{des} = 0$. Then, the error dynamics becomes

$$\begin{cases} \dot{\boldsymbol{e}}_{i1} = \boldsymbol{e}_{i2} \\ \dot{\boldsymbol{e}}_{i2} = \boldsymbol{f}_i + B_i \boldsymbol{u}_i \end{cases} \tag{18}$$

Theorem I: The system given in Eq. (18) is asymptotically stable with the controller in the form of

$$\boldsymbol{u}_i = B_i^{-1}(-\boldsymbol{f}_i - \lambda_1 \boldsymbol{e}_{i1} - \lambda_2 \boldsymbol{e}_{i2}) \tag{19}$$

where λ_1 and λ_2 are diagonal positive definite matrices.

The proof of theorem I can be obtained using the Lyapunov stability theory. Here, the Lyapunov function for each individual robot is chosen as

$$V_i = \frac{1}{2}\lambda_1 \boldsymbol{e}_{i1}^T \boldsymbol{e}_{i1} + \frac{1}{2}\boldsymbol{e}_{i2}^T \boldsymbol{e}_{i2} \geq 0 \tag{20}$$

Then, the time derivative of V_i becomes

$$\begin{aligned} \dot{V}_i &= \boldsymbol{e}_{i1}^T \dot{\boldsymbol{e}}_{i1} + \boldsymbol{e}_{i2}^T \dot{\boldsymbol{e}}_{i2} \\ &= \boldsymbol{e}_{i1}^T \boldsymbol{e}_{i2} + \boldsymbol{e}_{i2}^T (\boldsymbol{f}_i + B_i \boldsymbol{u}_i) \end{aligned} \tag{21}$$

Substitute (19) into (21), we have

$$\begin{aligned} \dot{V}_i &= \boldsymbol{e}_{i1}^T \dot{\boldsymbol{e}}_{i1} + \boldsymbol{e}_{i2}^T \dot{\boldsymbol{e}}_{i2} = \boldsymbol{e}_{i1}^T \boldsymbol{e}_{i2} + \boldsymbol{e}_{i2}^T (\boldsymbol{f}_i + B_i \boldsymbol{u}_i) \\ &= \boldsymbol{e}_{i1}^T \boldsymbol{e}_{i2} + \boldsymbol{e}_{i2}^T (-\lambda_1 \boldsymbol{e}_{i1} - \lambda_2 \boldsymbol{e}_{i2}) \\ &= -\lambda_2 \boldsymbol{e}_{i2}^T \boldsymbol{e}_{i2} \leq 0 \end{aligned} \tag{22}$$

Since, V_i is positive definite and $\dot{V}_i$ is negative definite, according to the Lyapunov stability theory, we can conclude that the system is asymptotically stable.

B. *Cooperative Control Law*

The cooperative control law is obtained by adding a cooperative term to the self-stabilization control law in Eq. (19)

$\boldsymbol{u}_i = B_i^{-1}[-\boldsymbol{f}_i - (\lambda_1 - \lambda_3)\boldsymbol{e}_{i1} - \lambda_2 \boldsymbol{e}_{i2} - \lambda_3 \sum_{j=1}^{n}(\boldsymbol{e}_{i1} - \boldsymbol{e}_{j1})]$, which can also be written as

$$\boldsymbol{u}_i = B_i^{-1}\left(-\boldsymbol{f}_i - \lambda_1 \boldsymbol{e}_{i1} - \lambda_2 \boldsymbol{e}_{i2} - \lambda_3 \sum_{j=1}^{n} \boldsymbol{e}_{j1}\right) \tag{23}$$

where λ_1, λ_2, λ_3, and $(\lambda_1 - \lambda_3)$ are all diagonal positive definite matrices.

The proof of the stability of the system starts from choosing the Lyapunov function as

$$\begin{aligned} V &= \frac{1}{2}\lambda_1 \sum_{i=1}^{n} \boldsymbol{e}_{i1}^T \boldsymbol{e}_{i1} + \frac{1}{2}\lambda_3 \left(\sum_{i=1}^{n} \boldsymbol{e}_{i1}\right)^T \left(\sum_{i=1}^{n} \boldsymbol{e}_{i1}\right) \\ &+ \frac{1}{2}\sum_{i=1}^{n} \boldsymbol{e}_{i2}^T \boldsymbol{e}_{i2} + \frac{1}{2}\lambda_1 \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\boldsymbol{e}_{i1} - \boldsymbol{e}_{j1}\right)^T \left(\boldsymbol{e}_{i1} - \boldsymbol{e}_{j1}\right) \\ &+ \frac{1}{2}\sum_{i=1}^{n} \sum_{j=1}^{n} \left(\boldsymbol{e}_{i2} - \boldsymbol{e}_{j2}\right)^T \left(\boldsymbol{e}_{i2} - \boldsymbol{e}_{j2}\right) \end{aligned} \tag{24}$$

Take derivative of the Lyapunov function,

$$\begin{aligned} \dot{V} &= \lambda_1 \sum_{i=1}^{n} \boldsymbol{e}_{i1}^T \boldsymbol{e}_{i2} + \lambda_3 \sum_{i=1}^{n} \boldsymbol{e}_{i1}^T \sum_{i=1}^{n} \boldsymbol{e}_{i2} \\ &+ \sum_{i=1}^{n} \boldsymbol{e}_{i2}^T (\boldsymbol{f}_i + B_i \boldsymbol{u}_i) \\ &+ \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\boldsymbol{e}_{i1} - \boldsymbol{e}_{j1}\right)^T \left(\boldsymbol{e}_{i2} - \boldsymbol{e}_{j2}\right) \\ &+ \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\boldsymbol{e}_{i2} - \boldsymbol{e}_{j2}\right)^T \left[(\boldsymbol{f}_i + B_i \boldsymbol{u}_i) - \left(\boldsymbol{f}_j + B_j \boldsymbol{u}_j\right)\right] \\ &= \lambda_1 \sum_{i=1}^{n} \boldsymbol{e}_{i1}^T \boldsymbol{e}_{i2} + \lambda_3 \sum_{i=1}^{n} \boldsymbol{e}_{i1}^T \sum_{i=1}^{n} \boldsymbol{e}_{i2} \\ &+ \sum_{i=1}^{n} \boldsymbol{e}_{i2}^T \left(-\lambda_1 \boldsymbol{e}_{i1} - \lambda_2 \boldsymbol{e}_{i2} - \lambda_3 \sum_{j=1}^{n} \boldsymbol{e}_{j1}\right) \\ &+ \lambda_1 \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\boldsymbol{e}_{i1} - \boldsymbol{e}_{j1}\right)^T \left(\boldsymbol{e}_{i2} - \boldsymbol{e}_{j2}\right) \\ &+ \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\boldsymbol{e}_{i2} - \boldsymbol{e}_{j2}\right)^T \Big((-\lambda_1 \boldsymbol{e}_{i1} - \lambda_2 \boldsymbol{e}_{i2} - \\ &\lambda_3 \sum_{k=1}^{n} \boldsymbol{e}_{k1}) - (\lambda_1 \boldsymbol{e}_{j1} - \lambda_2 \boldsymbol{e}_{j2} - \lambda_3 \sum_{k=1}^{n} \boldsymbol{e}_{k1})\Big) \\ &= -\lambda_2 \sum_{i=1}^{n} \boldsymbol{e}_{i2}^T \boldsymbol{e}_{i2} \\ &\quad -\lambda_2 \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\boldsymbol{e}_{i2} - \boldsymbol{e}_{j2}\right)^T \left(\boldsymbol{e}_{i2} - \boldsymbol{e}_{j2}\right) \leq 0 \end{aligned} \tag{25}$$

According to the Lyapunov stability theory, $V \geq 0$, $\dot{V} \leq 0$, the equal sign is valid if and only if the states become zeros. It can be concluded that the closed loop system is asymptotically stable.

IV. Simulation Results

The cooperative hunting control system is tested under a simulated environment. The hunting group is composed of three non-holonomic robots. MATLAB/Simulink® is used to program and run the simulation.

The initial positions of the target and three robots are $\boldsymbol{x}_{p0} = \{0,0\}^T m$, $\boldsymbol{x}_{10} = \{-30,40\}^T m$, $\boldsymbol{x}_{20} = \{0,50\}^T m$, and $\boldsymbol{x}_{30} = \{50,0\}^T m$. The initial velocities and orientations are $v_{p0} = 10\ m/s$, $\theta_{p0} = \frac{\pi}{3}$, $v_{10} = v_{20} = v_{30} = 0\ m/s$, $\theta_{10} = \theta_{20} = 0$, $\theta_{30} = \pi$. The control gains used in the simulations are $\lambda_1 = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.13 \end{bmatrix}$, $\lambda_2 = \begin{bmatrix} 0.5 & 0 \\ 0 & 1 \end{bmatrix}$, and $\lambda_3 = \begin{bmatrix} 0.003 & 0 \\ 0 & 0.001 \end{bmatrix}$.

The following two cases were tested, first, the target escapes along a fixed unknown trajectory as described below in case A, and second, the target escapes in a reactive way as described below in case B.

A. *The prey escapes with fixed but unknown trajectory*

In this case, the prey escapes along a straight line with a speed of $10\ m/s$ and an orientation angle of $\frac{\pi}{3}$. Figure 3 shows the trajectories of the prey and hunting robots. The relative positions (i.e., distance, angle of line of sight) are shown in Figure 4. It can be seen that the hunting group can successfully capture the target in 30 seconds. Figure 5 shows the orientation angles of the hunting robots converge to the orientation angle of the target in 12 seconds. The corresponding control signals (i.e., acceleration and angular rate) are given in Figure 6.

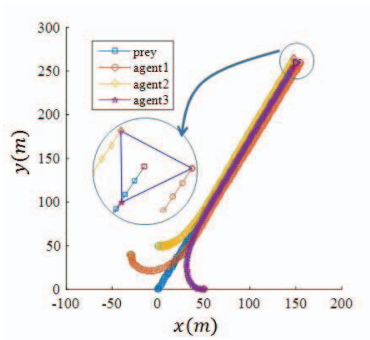


Figure 3. Case I: Trajectories of the prey and hunting robots

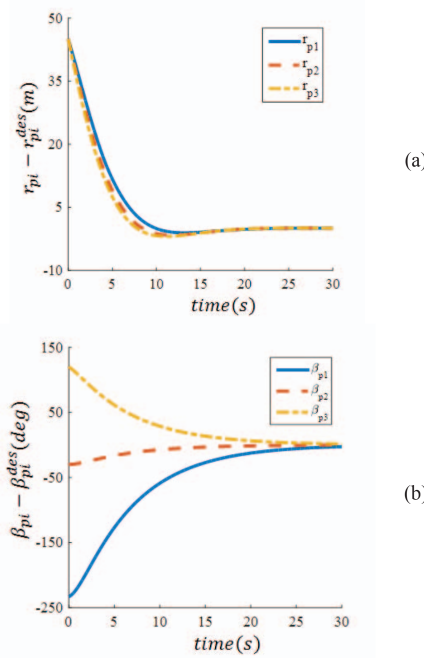


Figure 4. Case I: Relative position (a) the difference between the relative distance and desired value and (b) the difference between the angle of line of sight and desired value

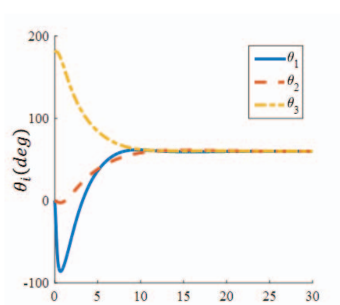


Figure 5. Orientation of the hunting robots

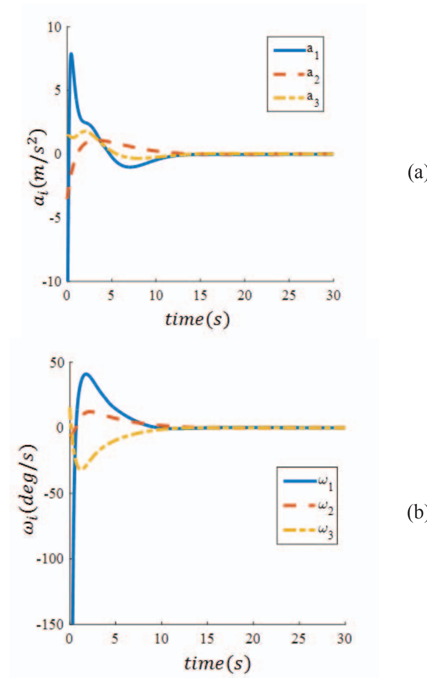


Figure 6. Case I: Robot acceleration (a) and angular rate (b)

B. The prey escapes using reactive maneuvers

In the reactive escaping, the direction of steering follows gradient of threat from the hunting robots, which is given by

$$\omega_p = K_\omega \left(\angle \left(\sum_{i=1}^{n} \frac{1}{r_{pi}^2} \boldsymbol{r}_{pi} \right) - \theta_p \right) \tag{26}$$

where $\angle(\ )$ represents direction of a vector. Note that $\angle\left(\sum_{i=1}^{n} \frac{1}{r_{pi}^2} \boldsymbol{r}_{pi}\right)$ is the direction of threat, which is also the ideal direction for the target to escape. The steering rate is linearly proportional to the difference between the direction of threat and its current orientation.

The initial conditions used in this case is exactly the same as those in the first case. The results show that the three hunting robots can capture the target with a relatively small error. The trajectories of the target and hunting robots are shown in Figure 7. Here, all three hunting robots are assumed to be within the range of detection of the prey. The prey flees with an initial direction of $\frac{\pi}{3}$ and steers away from the threat (three hunting robots). The relative positions during the whole capturing process are shown in Figure 8. It can been seen that the target are captured in 30 seconds.

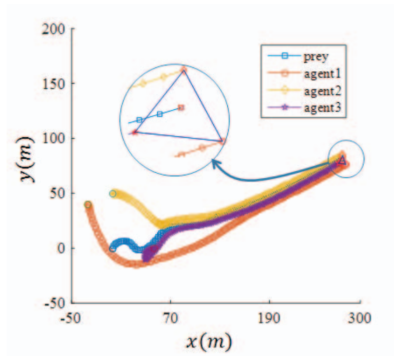
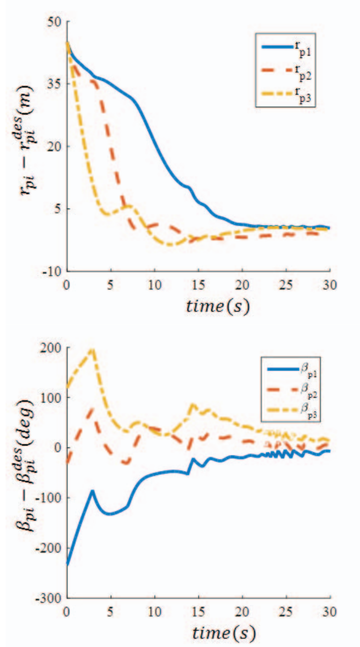


Figure 7. Case II: Trajectories of the prey and hunting robots



(a)

(b)

Figure 8. Case II: Relative position (a) the difference between the relative distance and desired value and (b) the difference between the angle of line of sight and desired value

V. DISCUSSION AND CONCLUSION

This paper studies a Lyapunov based cooperative hunting using multiple non-holonomic robots. The relative dynamics is formulated according to the kinematics relationship between the target and hunting robots. According to the dynamics model, a Lyapunov based cooperative controller is obtained by adding a cooperative term to the individual self-stabilization control law. The closed-loop system is proved to be asymptotically stable.

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