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A Robust leader-obstacle formation control

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Abstract—**This paper presents a new strategy for obstacle avoidance in mobile robots leader-follower formation. The key feature of the algorithm is that the system is robust against absolute acceleration of both leader and obstacle. On the other hand the angular velocity constraint of leader and obstacle is eliminated in the proposed leader-obstacle formation. The formation controller is composed of a feedback linearization part and a sliding mode compensator. Similar structure is used for both leader-follower and leader-obstacle formation. The proposed controller generates the commanded acceleration for the follower robot and makes the formation control system robust against the unmeasured acceleration of the leader robot and obstacle. Simulation results are presented to show the validity of the proposed methodology.**

I. INTRODUCTION

During the past several years, the research on control of a single mobile robot is replaced by the control of multiple mobile robots. There are several advantages in using a team of robots in tasks such as search and rescue operations, mapping unknown or hazardous environments, and security. Various control methods have been proposed and applied to the formation design of robotic networks, such as behavior-based approach [7, 8], virtual structure approach [9], and the leader-follower approach [1-3]. The leader-follower formation control of mobile robots, one of the main approaches in this field, has been studied by many researchers. In a robot formation with leader-follower configuration, one or more robots are selected as leaders, which are responsible for guiding the formation, and the rest of the robots are controlled to follow the leaders. The control objective is to make the follower robots track the leaders with some prescribed offsets.

Desai *et. al.*[1-3] presented a feedback linearization control method for the formation of nonholonomic mobile robots using the leader-follower approach. In [5], a robust method is presented to keep the follower in formation with leader and absolute acceleration of leader robot is treated as model uncertainty of the system.

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The focus of this paper is on obstacle avoidance during formation which means to keep the follower robot avoid collision with any obstacle, yet has desired formation with leader robot. In [4], a nonlinear feedback linearization method is used to active obstacle avoidance but in which angular velocity of leader and obstacle is considered, also follower robot must know acceleration of leader and obstacle. In [6], active obstacle avoidance is presented but obstacle has a constant velocity with no acceleration. The key point of our algorithm is that the system is robust against absolute acceleration of both leader and obstacle. On the other hand we eliminate the angular velocity of leader and obstacle in leader-obstacle formation. First, the kinematic model for leader-follower robot formation is formulated based on the relative motion states between the robots and the local motion of the follower robot. In Section 2, leader-follower formation is formulated based on kinematic equation of robots in formation. Equations of leader-obstacle formation is presented in Section 3 by considering obstacle as a virtual leader. In section 4, a formation controller, consisting of a feedback linearization part and a sliding mode compensator, is designed with a same design for both leader-follower and leader-obstacle formation. The proposed controller generates the commanded acceleration for the follower robot and makes the formation control system robust to the effect of unmeasured acceleration of the leader robot and obstacle. Simulation results in section 5 are used to validate the proposed methodologies.

II. FORMULATION OF LEADER-FOLLOWER FORMATION

In this section, the kinematics model of the leader-follower robots in formation is given. The leader-follower setup considered in this paper is presented in Fig. 1. The aim of the formation control is to make the follower robot R_2 track the leader robot R_1 with desired separation l_{12}^d and the desired relative bearing φ_{12}^d between the robots. And a relative motion sensor is mounted at point c on the follower robot R_2.

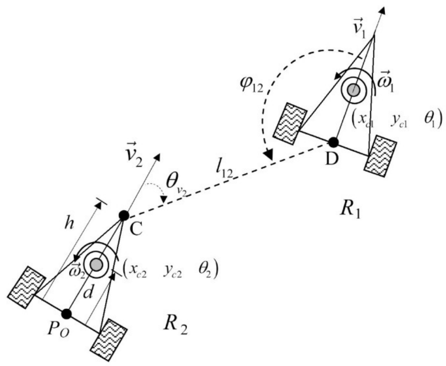


Fig. 1 Two robots in leader follower formation

The kinematic equations of the robots are given by the following equations:

$$\begin{cases} \begin{pmatrix} \dot{x}_{ci} \\ \dot{y}_{ci} \end{pmatrix} = \begin{pmatrix} cos\theta_i & -dsin\theta_i \\ sin\theta_i & dcos\theta_i \end{pmatrix} \begin{pmatrix} v_i \\ \omega_i \end{pmatrix} \\ \dot{\theta}_i = \omega_i \end{cases} \quad (1)$$

where $(x_{ci} \quad y_{ci})$ are the coordinates of the center of mass P_c in the world coordinates system, and θ_i is the heading angle of the robot. As shown in the Fig. 1,$\vec{v}_i$ and $\vec{\omega}_i$ are the linear and angular velocities of the robot R_i . P_0 is the intersection of the axis of symmetry with the driving wheel axis; d is the distance from the center of mass to point P_0 and h is the distance from the reference point C to point P_0 .

In [1-3] the kinematics of the leader and follower robots in formation is described by the following equations:

$$\dot{l}_{12} = v_2 cos\gamma - v_1 cos\psi_{12} + d\omega_2 sin\gamma$$

$$\dot{\psi}_{12} = \frac{1}{l_{12}}\{v_1 sin\psi_{12} - v_2 sin\gamma + d\omega_2 cos\gamma - l_{12}\omega_1\}$$

$$\dot{\theta}_{12} = \omega_1 - \omega_2 \quad (2)$$

where $\theta_{12} = \theta_1 - \theta_2$ and $\gamma = \theta_{12} + \varphi_{12}$.

Let set $\theta_{v2} = \pi - \varphi_{12} - \theta_{12}$ that is the relative bearing between velocity v_2 and line l_{12} and then rewrite (2) in the following form:

$$M(l_{12}, \theta_{v2}) \begin{pmatrix} \dot{l}_{12} \\ \dot{\varphi}_{12} \end{pmatrix} - N(l_{12}, \theta_{12}, \theta_{v2}) \begin{pmatrix} v_1 \\ \omega_1 \end{pmatrix} = \begin{pmatrix} v_2 \\ \omega_2 \end{pmatrix} \quad (3)$$

Where the matrices M and N are defined as:

$$M = \begin{pmatrix} -cos\theta_{v2} & -l_{12}sin\theta_{v2} \\ (sin\theta_{v2})/h & -(l_{12}cos\theta_{v2})/h \end{pmatrix}$$

$$N = \begin{pmatrix} -cos\theta_{12} & l_{12}sin\theta_{v2} \\ -(sin\theta_{12})/h & (l_{12}cos\theta_{v2})/h \end{pmatrix}$$

The follower robot does not know the absolute velocity of the leader robot and by solving (3), this velocity can be presented by the formation motion states and the absolute velocity of the follower robot:

$$N^{-1}\left[M\begin{pmatrix} \dot{l}_{12} \\ \dot{\varphi}_{12} \end{pmatrix} - \begin{pmatrix} v_2 \\ \omega_2 \end{pmatrix}\right] = \begin{pmatrix} v_1 \\ \omega_1 \end{pmatrix} \quad (4)$$

Differentiating (3) and incorporating (4) yields

$$\begin{pmatrix} \dot{v}_2 \\ \dot{\omega}_2 \end{pmatrix} = M\begin{pmatrix} \ddot{l}_{12} \\ \ddot{\varphi}_{12} \end{pmatrix} + C\begin{pmatrix} \dot{l}_{12} \\ \dot{\varphi}_{12} \end{pmatrix} - \dot{\theta}_{12}\begin{pmatrix} h\omega_2 \\ -v_2/h \end{pmatrix} + M\begin{pmatrix} -l_{12}\dot{\varphi}_{12} \\ \dot{l}_{12}/l_{12} \end{pmatrix}\omega_2 + \begin{pmatrix} \delta_1 \\ \delta_2 \end{pmatrix} \quad (5)$$

Where matrix C and vector δ are defined as:

$$C = \begin{pmatrix} \dot{\theta}_{v2}sin\theta_{v2} & -\dot{\theta}_{v2}l_{12}cos\theta_{v2} - \dot{l}_{12}sin\theta_{v2} \\ (\dot{\theta}_{v2}cos\theta_{v2})/h & (\dot{\theta}_{v2}l_{12}sin\theta_{v2} - \dot{l}_{12}cos\theta_{v2})/h \end{pmatrix}$$

$$\delta = \begin{pmatrix} \delta_1 \\ \delta_2 \end{pmatrix} = M\begin{pmatrix} -\dot{v}_1 cos\varphi_{12} \\ \dfrac{\dot{v}_1 sin\varphi_{12}}{l_{12}} - \dot{\omega}_1 \end{pmatrix}$$

Defining the state variables as $q = (l_{12} \quad \varphi_{12})^T$ and $\dot{q} = (\dot{l}_{12} \quad \dot{\varphi}_{12})^T$ and the input of the robot formation system as $u = (\dot{v}_2 \quad \dot{\omega}_2)^T$ we can rewrite model (5) in the following form:

$$\boldsymbol{u} = M(q, \theta_{12})\ddot{q} + C(q, \dot{q}, \theta_{12}, \dot{\theta}_{12})\dot{q} + G(q, \dot{q}, \theta_{12}, \dot{\theta}_{12}, v_2, \omega_2) + \delta(\dot{v}_1, \dot{\omega}_1, q, \dot{q}) \quad (6)$$

Where the vector $G(q, \dot{q}, \theta_{12}, \dot{\theta}_{12}, v_2, w_2)$ is defined as:

$$G = -\dot{\theta}_{12}\begin{pmatrix} h\omega_2 \\ -v_2/h \end{pmatrix} + M\begin{pmatrix} -l_{12}\dot{\varphi}_{12} \\ \dot{l}_{12}/l_{12} \end{pmatrix}\omega_2 \quad (7)$$

Equation (5) represents the input-output relation for the leader- follower robot formation system, where the outputs are the relative distance and the relative bearing and the relative velocities between robots. The inputs of the system are the absolute accelerations of the follower robot in local coordinates.

III. Formulation Of Leader-Obstacle Formation

Similar to the procedure used in Section 2, the kinematics model of the leader-obstacle formation is formulated in this section. The obstacle is considered as a virtual lead-robot (Fig. 2) and the aim of the formation control is to make the follower robot R_3 track the leader robot R_1 with the desired separation l_{13}^{d} and have a predetermined relative distancel_{23}^{d} with an accelerated obstacle R_2 .

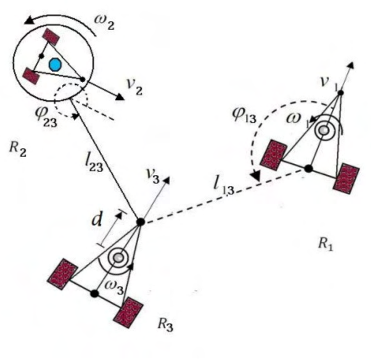


Fig. 2 Leader-obstacle formation

Similar to *l-l* control in [1], the kinematic equations for the system of leader-obstacle robots shown in Fig. 2 is given by :

$$\dot{x}_i = v_i cos\theta_i$$

$$\dot{y}_i = v_i sin\theta_i$$

$$\dot{\theta}_i = \omega_i \qquad (8)$$

For robot 1 and virtual robot 2 (i = 1,2). For the follower robot 3 we have:

$$\dot{l}_{13} = v_3 cos\gamma_1 - v_1 cos\varphi_{13} + d\omega_3 sin\gamma_1$$

$$\dot{l}_{23} = v_3 cos\gamma_2 - v_2 cos\varphi_{23} + d\omega_3 sin\gamma_2$$

$$\dot{\theta}_3 = \omega_3 \qquad (9)$$

where, $\gamma_i = \theta_i + \varphi_{i3} - \theta_3 \quad (i = 1{,}2)$.

Now, (9) can be expressed as:

$$\begin{bmatrix} \dot{l}_{13} \\ \dot{l}_{23} \end{bmatrix} = \begin{bmatrix} cos\gamma_1 & dsin\gamma_1 \\ cos\gamma_2 & dsin\gamma_2 \end{bmatrix} \begin{bmatrix} v_3 \\ \omega_3 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -cos\varphi_{23} & 0 \end{bmatrix} \begin{bmatrix} v_2 \\ \omega_2 \end{bmatrix} + \begin{bmatrix} -cos\varphi_{13} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ \omega_1 \end{bmatrix} \qquad (10)$$

Remark 1: what is important in leader-obstacle formation is the distance between the follower robot with both obstacle and leader robot and as can be seen from (10), the impact of angular velocity of the leader and the obstacle is not considered.

According to Remark 1, equation (10) can be simplified as below:

$$\begin{bmatrix} \dot{l}_{13} \\ \dot{l}_{23} \end{bmatrix} = \begin{bmatrix} cos\gamma_1 & dsin\gamma_1 \\ cos\gamma_2 & dsin\gamma_2 \end{bmatrix} \begin{bmatrix} v_3 \\ \omega_3 \end{bmatrix} + \begin{bmatrix} -cos\varphi_{13} & 0 \\ 0 & -cos\varphi_{23} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \qquad (11)$$

Solving equation (11) according to linear and angular velocity of follower robot yields

$$\begin{bmatrix} v_3 \\ \omega_3 \end{bmatrix} = M \begin{bmatrix} \dot{l}_{13} \\ \dot{l}_{23} \end{bmatrix} - N \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \qquad (12)$$

Were the matrices M and N are defined as *:*

$$M = \frac{1}{dsin(\gamma_2 - \gamma_1)} \begin{bmatrix} dsin(\gamma_2) & -dsin(\gamma_1) \\ -cos\,(\gamma_2) & cos\,(\gamma_1) \end{bmatrix}$$

$$N = \frac{1}{dsin(\gamma_2 - \gamma_1)} \begin{bmatrix} -dcos(\varphi_{13})sin\,(\gamma_2) & dsin(\gamma_1)cos\,(\varphi_{23}) \\ cos\,(\gamma_2)cos\,(\varphi_{13}) & -cos\,(\gamma_1)cos\,(\varphi_{23}) \end{bmatrix}$$

By solving (12) linear velocity of leader and obstacle (virtual leader) can be presented by formation motion states and absolute velocity of follower robot:

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = N^{-1} \left[M \begin{bmatrix} \dot{l}_{13} \\ \dot{l}_{23} \end{bmatrix} - \begin{bmatrix} v_3 \\ \omega_3 \end{bmatrix} \right] \qquad (13)$$

Similar to the procedure in Section 2, differentiating (12) and incorporating (13) yields in:

$$\begin{bmatrix} \dot{v}_3 \\ \dot{\omega}_3 \end{bmatrix} = M \begin{bmatrix} \ddot{l}_{13} \\ \ddot{l}_{23} \end{bmatrix} + C \begin{bmatrix} \dot{l}_{13} \\ \dot{l}_{23} \end{bmatrix} - C' \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} \qquad (14)$$

Where δ is defined as:

$$\delta = \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} = -N \begin{bmatrix} \dot{v}_1 \\ \dot{v}_2 \end{bmatrix}$$

Introducing the state variables as $q = [l_{13} \;\; l_{23}]^T$ and $\dot{q} = \left[\dot{l}_{13} \;\; \dot{l}_{23}\right]^T$ and the input of the formation system as $u = [\dot{v}_3 \;\; \dot{\omega}_3]^T$ we can rewrite model (14) in the following standard form:

$$u = M(\gamma_1, \gamma_2)\ddot{q} + C(\gamma_1, \gamma_2, \dot{\gamma}_1, \dot{\gamma}_2)\dot{q} + G(\gamma_1, \gamma_2, \dot{q}, v_3, \omega_3) + \delta(\gamma_1, \gamma_2, \dot{v}_1, \dot{v}_2) \qquad (15)$$

Where $G(\gamma_1, \gamma_2, \dot{q}, v_3, \omega_3)$ is defined as:

$$G = -C' \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$$

Equation (15) represents the input-output relation for the leader- obstacle formation system.

Remark 2 The second order kinematics model (6) and (15) forms a nonlinear and multivariable system, which allows us to do more rigorous analysis of the performance of control system, and to design robust nonlinear control laws that guarantees the global stability and tracking of more complex trajectories than those for the first order kinematics model.

Remark 3 The last term δ in (6) and (15) represents the effect of the absolute acceleration of leader robots, which is difficult to accurately measure or estimate due to the limitation of the motion sensors and treated as model uncertainty of the system.

Remark 4 There should be a formation switching system to switch formation from leader-follower to leader-obstacle when the follower senses an obstacle. For example, we can define control graphs [2], or use supervisory control of discrete event systems[4].

IV. THE PROPOSED ROBUST FORMATION CONTROL SCHEME

In this section, a robust controller is designed to stabilize the system in the presence of modeling uncertainties. The procedure used is similar to what exerted in [5] for $l-\varphi$ formation.however as it is obvious from discussion given in previous section our model is based on l-l formation.

Remark 5 Since the models (6) and (15) have the same structure, this controller has a same design for both leader-follower or leader-obstacle formation.

The objective is to develop a control law to determine u for the formation system such that the follower robot tracks the leader robot(s) with a given formation configuration q_d.The proposed control scheme consists of a nominal part designed based on the nominal model of the system without the perturbation of modeling uncertainty and a sliding mode robust compensator to stabilize the overall system in the presence of uncertainty. The overall control is defined as

$$\begin{cases} u = u_0 + u_1 \\ u_0 = M\ddot{q}_r + C\dot{q} + G \\ u_1 = -M\eta sgn(s) \end{cases} \qquad (16)$$

where u_0 is the nominal control, and u_1 is a sliding mode compensator. Their design is described in the following. The new reference acceleration vector $\ddot{q}_r$ is formed by shifting the desired acceleration $\ddot{q}_r$ according to the position error $\tilde{q}$ and velocity error $\dot{\tilde{q}}$.

$$\ddot{q}_r = \ddot{q}_d - \Lambda_2\dot{\tilde{q}} - \Lambda_1\tilde{q} \qquad (17)$$

where $\Lambda_i = diag(\lambda_{i1} \;\; \lambda_{i2})$ for $i = 1,2$ are symmetric positive definite matrices. Thus, the reference trajectory is expressed in terms of the tracking errors. The component of the constant vector η satisfies $\eta_i > [|M^{-1}\delta|]_i + \eta_{0i}$ where η_{0i} is a strictly positive constant.

The nominal control u_0 in (16) leads to a linear closed-loop equation of the nominal system

$$\ddot{\tilde{q}} = -\Lambda_2\dot{\tilde{q}} - \Lambda_1\tilde{q} \qquad (18)$$

and control law (16) results in the actual closed-loop system of (6) and (15)in the form of

$$\ddot{q} = \ddot{q}_r - \boldsymbol{\eta} sgn(s) - M^{-1}\delta \qquad (19)$$

Define the tracking errors as $z_i = [\tilde{q}_i \;\; \dot{\tilde{q}}_i]^T$ for $i = 1,2$ then, the closed-loop equation can be written as

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix}\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} - \begin{bmatrix} 0 \\ [\boldsymbol{\eta} sgn(s) + M^{-1}\delta]_1 \\ 0 \\ [\boldsymbol{\eta} sgn(s) + M^{-1}\delta]_2 \end{bmatrix} \qquad (20)$$

where

$$A_i = \begin{bmatrix} 0 & 1 \\ -\lambda_{i1} & -\lambda_{i2} \end{bmatrix}, \qquad i = 1,2$$

Let P_i be the symmetric positive definite solution of the following Lyapunov equation

$$A_i^T P_i + P_i A_i = -Q_i, \quad i = 1,2 \qquad (21)$$

where Q_1 and و Q_2 are symmetric positive defnite matrices. Let ¸$\lambda_{min}(Q_i)$ denote the smallest eigenvalue of the matrix Q_i . The stability of the resultant closed-loop (20) can be proved using the Lyapunov theory.

Theorem 1 The closed-loop system (20) under control law (16) is asymptotically stable at the origin with the variable s_i in (16) selected as.

$$s_i = [z_i^T P_i]_2 \quad , \qquad i = 1,2 \qquad (22)$$

where $[z_i^T P_i]_2$ denotes the second element of the vector $z_i^T P_i$.

Proof. Consider the composite Lyapunov function candidate

$$V(t)=\frac{1}{2}\sum_{i=1}^{2} z_i^T P_i z_i \qquad (23)$$

Differentiating (23) with time along the solutions of (20), substituting $z_i^T P_i$
with s_i from (22), we have

$$\dot{V}(t)=\frac{1}{2}\sum_{i=1}^{2}(\dot{z}_i^T P_i z_i + z_i^T P_i \dot{z}_i)$$

$$=\sum_{i=1}^{i=2}\left\{-\frac{1}{2}z_i^T Q_i z_i - z_i^T P_i\begin{bmatrix}0\\ \eta_i sgn(s_i)+(M^{-1}\delta)_i\end{bmatrix}\right\}$$

$$\leq -0.5\sum_{i=1}^{2}\lambda_{min}(Q_i)\|z_i\|^2$$

$$-\sum_{i=1}^{2}\eta_{0i}|s_i| \qquad (24)$$

From the last equation of (24), we have $V(\dot{t}) < 0$ Thus, Theorem 1 is proved.

Remark 6. Note that the follower robot tracks the leader with a predescribed formation and upon sensing an obstacle, switches its controller to leader-obstacle formation. In this case, it does not care about its relative bearing with the leader robot, hence it tries to have a predetermined distance with both obstacle(to avoid it) and leader robot. When obstacle goes away from the follower robot, by switching the controller, follower robot can again return to its prime formation with the leader robot.

Remark7.There is a configuration in which $\theta_2-\theta_1=\varphi_{13}-\varphi_{23}$ .in this case the matrices M and N lie in singular situation and the results may be inaccurate. This situation is shown in simulation section.

V. SIMULATION RESULTS

We will now illustrate the effectiveness of the proposed control scheme. Simulation results in MATLAB environment confirm the validity of the presented approach. In the first scenario, leader-follower formation is used.
The desired formation is defined as:

$$q_{des}=[l_{12}^d\ ,\ \varphi_{12}^d]^T=[400\ ,\ \frac{2\pi}{3}]^T$$

Where h is set at $h=100\ mm$ .The trajectories of the two robots are depilcted in Fig. 3. Where the leader robot has a circular path.

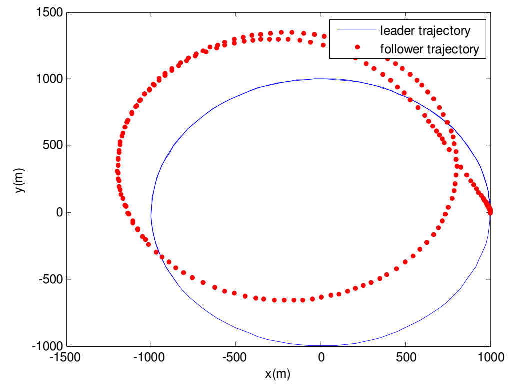
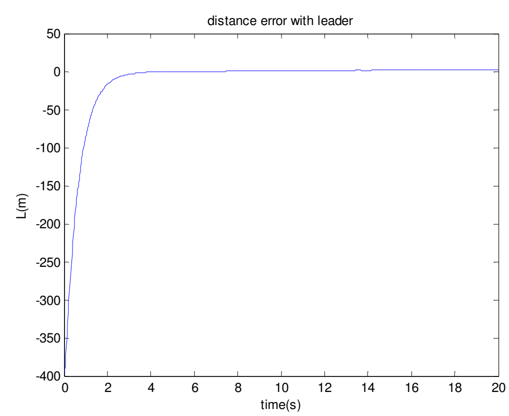


Fig. 3 Trajectory of leader-follower formation

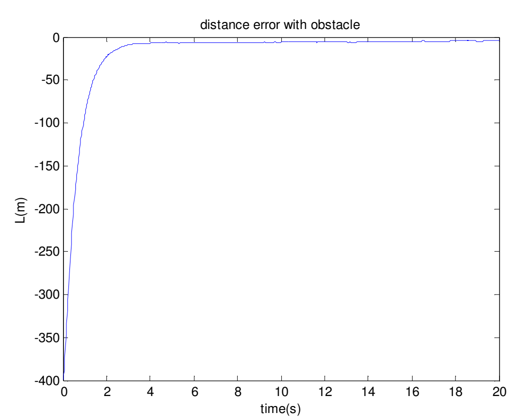
In the second experiment, the leader-obstacle formation is used. the desired formation is defined as:

$$q_{des}=[l_{13}^d\ ,\ l_{23}^d]^T=[400\ ,\ \ 400]^T$$

Distance errors are shown in Fig. 4



(a)

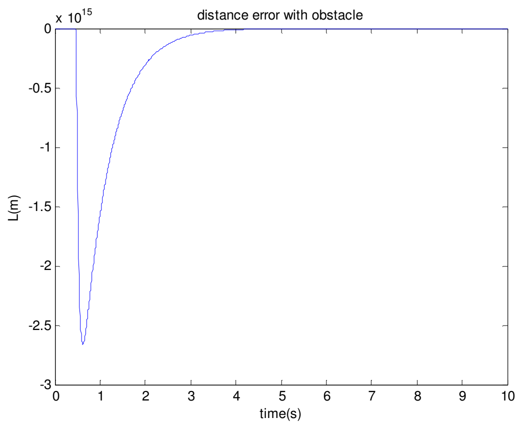


(b)

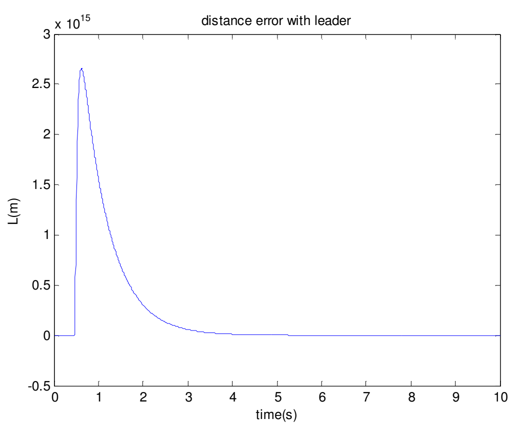
Fig. 4 The Distance errors in leader-obstacle formation

Distance error between follower and leader (Fig.4.a) and distance error between follower and obstacle (Fig.4.b) both converge to zero and this means when an obstacle is nearing to leader-follower configuration, the follower robot avoid it and has a predetermined distance into leader and obstacle.

Fig. 5 shows the distance errors in singular situation as mentioned in Remark 7.



(a)



(b)

Fig. 5 The distance errors in singular situation, a) between follower and obstacle, b) between follower and leader

VI. Conclusions

In This paper, we presented a new strategy for obstacle avoidance in leader-follower formation in which, an obstacle is considered as a virtual leader. Based on the second order kinematics model, a robust controller is proposed to control the leader-obstacle formation using only the relative measurement of the motion states between robots. The proposed controller does not need global sensor for formation control, and makes the closed-loop formation system robust to the uncertainty associated with the absolute acceleration of both leader robot and obstacle. We also eliminate the angular velocity of leader and obstacle in formulation of leader-obstacle formation. Simulation results demonstrated the effectiveness of the proposed method.

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