Formation Control of Unmanned Surface Vehicles with Vision Sensor Constraints

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***Abstract*—This paper presents a practical formation control strategy for unmanned surface vehicles (USVs) under sensor constraints with no communication interchange. The team of USVs equipped with monocular visions are modeled in a Leader-Follower (L-F) formation. The formation controller relies on line-of-sight (LOS) range and bearing information received from the forward looking camera. The onboard vision sensor is assumed to be able to measure the range and bearing information of the leader, and the vision sensor's capability is restricted due to limited Field of View (FOV) and visual range. An outer-loop backstepping controller is first designed to stabilize the formation, then an inner-loop controller is designed to cope with the sensor constraints in order not to lose the leader's information. The proposed controller guarantees that the formation is always maintained. The effectiveness of the proposed strategy is demonstrated by numerical simulations.**

Keywords*—*unmanned surface vehicle (USV); formation control; Leader-Follower (L-F); sensor constraints

I. INTRODUCTION

The formation control of multi-vehicle systems has gained enormous interest in the research of system and control. This is partially due to its proficient in performing difficult tasks, such as costal patrols, environmental monitoring, disaster search. The relevant applications have arisen in marine engineering include collaborative anti-submarine, surveillance of territorial waters, underway ship replenishment[1], etc. Therefore the coordination and formation control of multiple marine vehicles has been and still remains an active topic of research[2]. Many researchers have made contributions to the formation control, and several methods have been proposed include leader-follower method[1][3~6], virtual structure strategy[7][8], behavior-based approach[9][10], graph theory-based method[11][12][13], artificial potential method[14], and so on.

The Leader-Follower (L-F) method is most preferred in practice because of its simplicity and scalability[4]. In an L-F formation, one or more individual of the group is designated as the leader, and the others are designated as followers, the followers follow the leader to keep the desired distance or angle, then the formation will be achieved ultimately. During the last decade, the formation control has been focused on the marine vehicles, and most of works appear to have been done within the L-F framework. In [15], nonlinear formation control of marine craft is considered, and vectorial backstepping is employed to solve the geometric task and the dynamic task. A method for formation control of marine surface craft inspired by Lagrangian mechanics is presented in [16], and the method is also suitable for underactuated ships. In [17], sliding mode control laws for L-F formation control of multiple USVs in arbitrary formations are proposed. Within an L-F framework, fully actuated ships are controlled as a formation by applying the integrator backstepping and cascade theory in [18]. In [19], the problem of path following and formation control for underactuated surface vessels in the presence of unknown ocean currents is considered, and the proposed controllers are based on LOS guidance, adaptive control, and cascaded systems theory. In [5], formation control of multiple underactuated autonomous underwater vehicles (AUVs) is concerned, where a virtual vehicle is constructed such that its trajectory converges to the reference trajectory of the follower. In [20], a linear consensus protocol is proposed for networked multiagents, the whole group dynamics is regarded as a time-varying system. A robust adaptive formation controller is developed by employing neural network and dynamic surface control technique to keep the underactuated autonomous surface vehicles (ASVs) moving in an L-F formation in [1], where the proposed method only uses the measurements of LOS range and angle by local sensors. An algorithm is proposed for formation control in absence of leader's velocity information in [21]. In [22], a new implementable cooperative adaptive backstepping controller is proposed for a group of AUVs to track a time-varying virtual leader, where the singular perturbation theory is also used so that the neighbour's velocity information is precluded in the cooperative design. In [23], the control of the leader is designed for tracking the desired path by Pontryagin Maximum principle, and the followers are moving to follow the leader's path under the optimal tracking control. In [24], the neural network and approach angle are used to implement formation control of AUVs without the velocity information of the leader. An optimal path for landmark-based navigation by differential-drive robots with Field-of-View (FOV) constraints is proposed in [25], where only one vehicle is considered. In [2], the proposed control design employs dipolar vector fields and a viability-based switching control scheme, considering that the sensing capabilities are restricted, due to limited range and angle-of-view, however the method

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assumes that the leader's velocity is a priori known to the follower.

In general, among those control designs, two types of methods can be summarized. One type for L-F formation control needs communication information between leaders and followers, and deals with the problems caused by communication delay, packet lose[26][27], etc. Another type for L-F formation control requires the local sensors such as radar and sonar to measure the vehicles' states, and copes with noises which are bad for measurements. However, most of the researchers assumed that there were no constraints with the sensors they used, which is not practical.

Sensor constraints is a common problem which has not been well handled in marine engineering. In this paper, we proposed a framework to solve this problem, which is simple and practically useful. Three USVs equipped with monocular visions are modeled in an L-F formation using Cartesian coordinates as shown in [28]. We assume that no information is exchanged between each vehicle, and the vision sensor has constraints which is to say the sensor's capability is restricted, and the onboard vision sensor is able to measure the range and bearing information relative to the leader. In order to keep the formation of the USVs with sensor constraints, a control hierarchy with double feedback loops is adopted. To get the desired formation, a controller based on backstepping method is designed in the outer-loop which takes charge of the kinematics control of the formation and the dynamics control of the USVs. In the inner-loop, the traditional Proportion-Integration-Differentiation (PID) controller is used to keep the followers tracking the leader so that the formation will always be maintained even if there are sensor constraints.

The rest of the paper is organized as follows. In Section 2, the modeling of the system is provided and the sensor constraints are stated. Section 3 shows the practical formation control of the system. In Section 4, simulation results are shown. Section 5 is the conclusion.

II. Problem Formulation and Preliminaries

This section describes the kinematic and dynamic model of the USVs, and provides the L-F formation model using Cartesian coordinates. The sensor constraints problem and some definitions are introduced.

A. Vehicle Modeling

Assuming that the inertia, added mass, and hydrodynamic damping matrices are diagonal, which holds good for ships having port/starboard and fore/aft symmetry, and neglecting the motions in heave, roll, and pitch, the kinematics and dynamics of the USV without no external disturbances can be described as follows[29]:

$$\begin{cases} \dot{x} = u\cos(\psi) - v\sin(\psi) \\ \dot{y} = u\sin(\psi) + v\cos(\psi) \\ \dot{\varphi} = r \end{cases}, \tag{1}$$

$$\begin{cases} \dot{u} = m_2/m_1 vr - d_1/m_1 u + 1/m_1 \tau_u \\ \dot{v} = -m_1/m_2 ur - d_2/m_2 v \\ \dot{r} = (m_1 - m_2)/m_3 uv - d_3/m_3 r + 1/m_3 \tau_r \end{cases}. \tag{2}$$

Here, (x, y) denotes the position and φ is the heading angle of the USV in the earth-fixed frame; u, v and r are the velocities of the USV in the body-fixed frame (u: surge velocity, v: sway velocity, r: angular velocity in yaw); $m_i (i = 1,2,3)$ are the inertia of the USV including added masses; $d_i (i = 1,2,3)$ are the hydrodynamic damping in surge, sway and yaw; τ_u and τ_r are the control signal (τ_u: surge force, τ_r: yaw moment). For the actual USV, the velocity and input force are limitied, so we make the following assumption.

Assumption 1. The velocities and input forces of the USV are bounded as $\sup_t \| u \| = \overline{u}_{\max}$, $\sup_t \| v \| = \overline{v}_{\max}$, $\sup_t \| r \| = \overline{r}_{\max}$, $\sup_t \| \tau_u \| = \overline{\tau}_{u\max}$, $\sup_t \| \tau_r \| = \overline{\tau}_{r\max}$ with known bound $\overline{u}_{\max} > 0$, $\overline{v}_{\max} > 0$, $\overline{r}_{\max} > 0$, $\overline{\tau}_{u\max} > 0$ and $\overline{\tau}_{r\max} > 0$.

B. Leader-Follower Formation

In this paper, the leader vehicle will be denoted with a subscript 'L', while the i-th follower vehicle will be denoted with a subscript 'Fi'. Fig. 1 presents the basic geometric structure of two USVs moving in the L-F formation in Cartesian coordinates, where (X_L, Y_L, φ_L) is the position and yaw angle of the *Leader*, $(X_{Fi}, Y_{Fi}, \varphi_{Fi})$ is the position and yaw angle of the *Follower i*, (l_{LFi}, λ_{LFi}) denotes the LOS range and bearing information between the *Leader* and the *Follower i*. The formation is defined as

$$\mathbb{F}_{LFi} = [l_{LFi} \quad \lambda_{LFi}]^T, \tag{3}$$

where $l_{LFi} \in \mathbb{R} > 0$, $\lambda_{LFi} \in [0, \pi]$.

The desired formation is defined as

$$\mathbb{F}_{LFi}^d = [l_{LFi}^d \quad \lambda_{LFi}^d]^T. \tag{4}$$

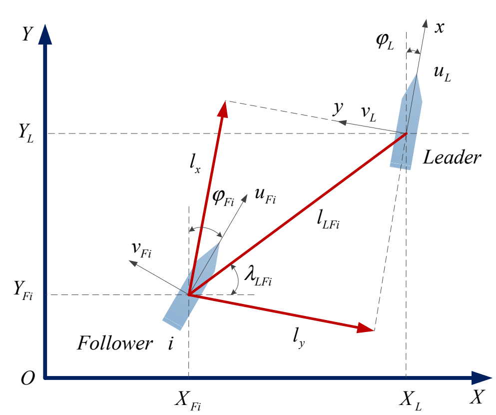

Fig. 1. Leader-Follower formation

In Fig. 1, l_x and l_y are the projects of l_{LFi} along x and y directions relative to the leader. As long as (l_x, l_y) is fixed or controlled to be the desired value (l_x^d, l_y^d) and the orientation and relative position of the leader are given, the follower's position will be unique. So the desired formation $\mathbb{F}_{LFi}^d$ will be maintained. l_x and l_y are got as follows:

$$\begin{cases} l_x = (X_L - X_F)\cos\varphi_L + (Y_L - Y_F)\sin\varphi_L \\ l_y = -(X_L - X_F)\sin\varphi_L + (Y_L - Y_F)\cos\varphi_L \end{cases}, \tag{5}$$

$$l_x^d = l_{LFi}^d \sin(\lambda_{LFi}^d + \varphi_L)\,,\ l_y^d = l_{LFi}^d \cos(\lambda_{LFi}^d + \varphi_L)\,. \tag{6}$$

Combine (1) and (5), we can get the formation kinematics model as

$$\begin{cases} \dot{l}_x = u_L - u_F \cos e_\varphi - v_F \sin e_\varphi + l_y \dot{\varphi}_L \\ \dot{l}_y = v_L + u_F \sin e_\varphi - v_F \cos e_\varphi - l_x \dot{\varphi}_L \\ \dot{e}_\varphi = \dot{\varphi}_L - \dot{\varphi}_F = r_L - r_F \end{cases}. \tag{7}$$

The distance errors in x and y directions are defined as

$$e_x = l_x - l_x^d\,,\ e_y = l_y - l_y^d\,. \tag{8}$$

Combine (6), (7) and (8), then the error model of the system are given as

$$\begin{cases} \dot{e}_x = \dot{l}_x - \dot{l}_x^d = -u_F \cos e_\varphi - v_F \sin e_\varphi + e_y \dot{\varphi}_L \\ \qquad\qquad + u_L + l_y^d \dot{\varphi}_L - \dot{l}_x^d \\ \dot{e}_y = \dot{l}_y - \dot{l}_y^d = u_F \sin e_\varphi - v_F \cos e_\varphi - e_x \dot{\varphi}_L \\ \qquad\qquad + v_L - l_x^d \dot{\varphi}_L - \dot{l}_y^d \\ \dot{e}_\varphi = \dot{\varphi}_L - \dot{\varphi}_F = r_L - r_F \end{cases}. \tag{9}$$

Therefore, the control task is to design control algorithms for the followers such that

$$\lim_{t\to\infty} \| e_y \| = 0\,,\ \lim_{t\to\infty} \| e_x \| = 0\,, \tag{10}$$

$$\lim_{t\to\infty} e_\varphi = \Delta,\ \ \Delta \in (-\pi/2, \pi/2)\,, \tag{11}$$

where Δ always chooses 0, because in formation control the orientation of the follower is always kept being the same as the leader's.

C. Preliminaries

In this paper, three USVs equipped with forward-looking vision sensors are modeled, and each vision sensor is assumed to have FOV limitations. The circular sector of radius D_{range}

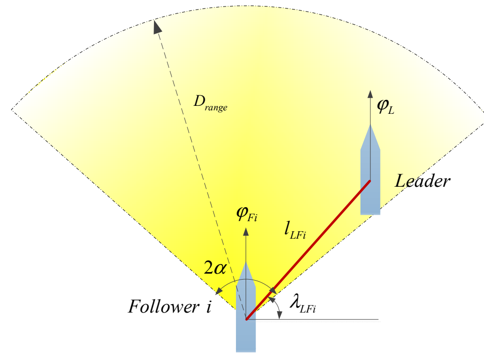

Fig. 2. Sensor constraints

and angle 2α as shown in Fig. 2 define the effective sensing area of each USV. Thus each vehicle can get the measurements of the objects moving within its sensing area. The two USVs shown in Fig. 2 can form a formation if and only if the *Follower i* maintain the sensing with the *Leader*.

To facilitate the control design, we make the following assumptions.

Assumption 2 The formation state vector $\mathbb{F}_{LFi}$ and leader's orientation is measured accurately by sensor. And the leader's velocities are assumed to be calculated from time derivative of the sensor measurement.

Assumption 3 The FOV of the onboard sensor has a constraint angle 2α. The visual range of the sensor d_v is bounded as $\sup(d_v) = D_{range}$. And the desired range l_{LFi}^d between leader and follower is bounded as $\sup(l_{LFi}^d) << D_{range}$.

Assumption 4 The orientation and velocities of each USV is known for itself. No disturbances and obstacles are considered in this formation system.

III. Practical Formation Control

This section presents the practical formation controllers designed with formation kinematics controller, dynamics controller and switching controller. In order to keep the formation of the USVs with sensor constraints, a control hierarchy with double feedback loops is adopted. In the outer-loop, the kinematics controller is designed to calculate the follower's desired forward speed u_F^d and desired angular velocity r_F^d to satisfy (10) and (11) so as to maintain the desired formation, and the dynamics controller is applied to make the USV generate desired input signals (τ_u^d : desired surge force, τ_r^d : desired yaw moment) to get the desired velocities (u_F^d and r_F^d). In the inner-loop, the traditional PID controller is used to keep the followers tracking the leader so that the formation will always be maintained since sensor constraints are concerned in this research. The control hierarchy of each individual USV is illustrated in Fig. 3.

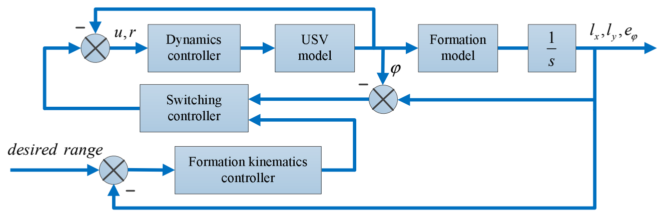

Fig. 3. The formation control hierarchy

A. Kinematics Control

A rotation matrix R_{e_φ} is defined firstly:

$$R_{e_\varphi} = -\begin{bmatrix} \cos e_\varphi & -\sin e_\varphi \\ \sin e_\varphi & \cos e_\varphi \end{bmatrix}. \tag{12}$$

Then we can rotate the distance errors in (8) to the follower's coordinate

$$\Sigma = R_{e_\varphi} E , \tag{13}$$

where $\Sigma = [\varepsilon_1, \varepsilon_2]^T$, $E = [e_x, e_y]^T$. Then we can get

$$\begin{cases} \dot{\varepsilon}_1 = u_F - \xi_1 \cos e_\varphi + \xi_2 \sin e_\varphi + \varepsilon_2 r_F \\ \dot{\varepsilon}_2 = v_F - \xi_1 \sin e_\varphi - \xi_2 \cos e_\varphi - \varepsilon_1 r_F \end{cases}, \tag{14}$$

where

$$\xi_1 = u_L + l_y^d \dot{\varphi}_L - \dot{l}_x^d \, , \; \xi_2 = v_L - l_x^d \dot{\varphi}_L - \dot{l}_y^d \, .$$

Step 1: Define the control Lyapunov function (CLF)

$$V_1 = 1/2\varepsilon_1^2 + 1/2\varepsilon_2^2 , \tag{15}$$

whose time derivative combined with (14) is given by

$$\begin{aligned} \dot{V}_1 = \varepsilon_1 \dot{\varepsilon}_1 + \varepsilon_2 \dot{\varepsilon}_2 = \varepsilon_1 (u_F - \xi_1 \cos e_\varphi + \xi_2 \sin e_\varphi) \\ + \varepsilon_2 (v_F - \xi_1 \sin e_\varphi - \xi_2 \cos e_\varphi) \end{aligned}. \tag{16}$$

Choose the kinematics control law as

$$u_F^d = -k_1 \varepsilon_1 + \xi_1 \cos e_\varphi - \xi_2 \sin e_\varphi , \tag{17}$$

$$v_F^d = -k_2 \varepsilon_2 + \xi_1 \sin e_\varphi + \xi_2 \cos e_\varphi , \tag{18}$$

where $k_1, k_2 > 0 \in \mathbb{R}$.

Then (16) becomes

$$\dot{V}_1 = -k_1 \varepsilon_1^2 - k_2 \varepsilon_2^2 \le 0 . \tag{19}$$

So the system is asymptotic stable.

Step 2: For an underactuated USV as shown in (2), there is no input control force to control the sway velocity, so we should design a controller to make $v_F \to v_F^d$ and $e_\varphi \to \Delta$ using the control signal τ_r .

Define the sway velocity error as

$$v_e = v_F - v_F^d , \tag{20}$$

whose time derivative combined with (2) and (18) is given by

$$\begin{aligned} \dot{v}_e &= \dot{v}_F - \dot{v}_F^d \\ &= -m_1 / m_2 u_F r_F - d_2 / m_2 v_F - \dot{v}_F^d \\ &= -m_1 / m_2 u_F r_F - d_2 / m_2 v_F \\ &\quad + k_2 (v_F - \xi_1 \sin e_\varphi - \xi_2 \cos e_\varphi - \varepsilon_1 r_F) \\ &\quad - \dot{\xi}_1 \sin e_\varphi - \dot{\xi}_2 \cos e_\varphi - \xi_1 \cos e_\varphi \dot{e}_\varphi + \xi_2 \sin e_\varphi \dot{e}_\varphi \, . \\ &= -d_2 / m_2 v_F - m_1 / m_2 k_1 \varepsilon_1 r_F + m_1 / m_2 \xi_1 \cos e_\varphi r_F \\ &\quad - m_1 / m_2 \xi_2 \sin e_\varphi r_F + k_2 v_F - k_2 \xi_1 \sin e_\varphi \\ &\quad - k_2 \xi_2 \cos e_\varphi - k_2 \varepsilon_1 r_F - \dot{\xi}_1 \sin e_\varphi - \dot{\xi}_2 \cos e_\varphi \\ &\quad - \xi_1 \cos e_\varphi \dot{e}_\varphi + \xi_2 \sin e_\varphi \dot{e}_\varphi \end{aligned} \tag{21}$$

Choose $k_1 = d_2 / m_1$ and $k_2 = d_2 / m_2$, then (21) becomes:

$$\begin{aligned} \dot{v}_e &= (m_1 / m_2 - 1)(\xi_2 \sin e_\varphi - \xi_1 \cos e_\varphi) r_F \\ &\quad - d_2 / m_2 (\xi_1 \sin e_\varphi + \xi_2 \cos e_\varphi) \\ &\quad + (\xi_2 \sin e_\varphi - \xi_1 \cos e_\varphi) r_L - \dot{\xi}_1 \sin e_\varphi - \dot{\xi}_2 \cos e_\varphi \end{aligned} . \tag{22}$$

Define the control Lyapunov function (CLF)

$$\dot{V}_2 = 1/2 v_e^2 + k_3 (1 - \cos e_\varphi), \; k_3 > 0 \in \mathbb{R} , \tag{23}$$

then we get the time derivative of (23), giving

$$\begin{aligned} \dot{V}_2 &= v_e \dot{v}_e + k_3 \sin e_\varphi (r_L - r_F) \\ &= v_e [(m_1 / m_2 - 1) \lambda r_F - d_2 / m_2 \zeta \\ &\quad + \lambda r_L - \dot{\xi}_1 \sin e_\varphi - \dot{\xi}_2 \cos e_\varphi] + k_3 \sin e_\varphi r_L - k_3 \sin e_\varphi r_F \end{aligned} , \tag{24}$$

where

$$\lambda = \xi_2 \sin e_\varphi - \xi_1 \cos e_\varphi \, , \; \zeta = \xi_1 \sin e_\varphi + \xi_2 \cos e_\varphi \, .$$

Choose the virtual control

$$r_F^d = r_L + k_4 \sin e_\varphi - k_5 (m_1 / m_1 - 1) v_e \lambda + \Theta , \tag{25}$$

where

$$\Theta = -\text{sgn}(v_e)\frac{[(k_4 + k_3k_5)\| m_1/m_2 - 1\| + d_2/m_2]\|\zeta\|}{\| m_1/m_2 - 1\|\|\zeta\| + k_3}.$$

Then (24) becomes

$$\begin{aligned}\dot{V}_2 &= -k_5(m_1/m_2-1)^2 v_e^2\lambda^2 - k_3k_4\sin^2 e_\varphi \\ &\quad + v_e[\lambda(m_1/m_2 r_L + m_1/m_2 - 1)(k_4+k_3k_5)\sin e_\varphi \\ &\quad - \dot{\xi}_1 \sin e_\varphi - \dot{\xi}_2\cos e_\varphi - d_2/m_2\zeta] \\ &\quad + [v_e(m_1/m_2-1)\lambda - k_3\sin e_\varphi]\Theta \\ &\le -k_5(m_1/m_2-1)^2 v_e^2\lambda^2 - k_3k_4\sin^2 e_\varphi \\ &\quad + \| v_e\|[\|\zeta\|(\| m_1/m_2 r_L\| \\ &\quad + \| m_1/m_2 - 1\|(k_4+k_3k_5) + d_2/m_2) + \|\dot{\xi}_1\| + \|\dot{\xi}_2\|] \\ &\quad + (\| v_e\|\| m_1/m_2-1\|\|\zeta\| + k_3)\Theta \\ &\le -k_5(m_1/m_2-1)^2 v_e^2\lambda^2 - k_3k_4\sin^2 e_\varphi + \sigma\end{aligned} \quad ,(26)$$

where σ is an arbitrary bounded infinitesimal constant, so the system (v_e, e_φ) is asymptotic stable.

B. Dynamics Control

The desired forward speed u_F^d and desired angular velocity r_F^d is known by the kinematics controller, then the dynamics controller should be designed to generate control signals for the USVs to make the vessels achieve the desired velocities so as to the formation will be established.

Step 1: Define the velocity error in surge as

$$u_e = u_F - u_F^d, \tag{27}$$

and its time derivative is

$$\dot{u}_e = m_2/m_1 v_F r_F - d_1/m_1 u_F + 1/m_1\tau_{uF} - \dot{u}_F^d. \tag{28}$$

Define the CLF as

$$V_3 = 1/2 u_e^2, \tag{29}$$

then the time derivative combined with (29) and (2) is given by

$$\dot{V}_3 = u_e(m_2/m_1 v_F r_F - d_1/m_1 u_F + 1/m_1\tau_{uF} - \dot{u}_F^d). \tag{30}$$

Choose the control law as

$$\tau_{uF} = m_1(-k_6 u_e - m_2/m_1 v_F r_F + d_1/m_1 u_F + \dot{u}_F^d),\ k_6 > 0 \in \mathbb{R}. \tag{31}$$

Equation (30) then becomes

$$\dot{V}_3 = -k_6 u_e^2 \le 0, \tag{32}$$

Step 2: Define the angle velocity error as

$$r_e = r_F - r_F^d, \tag{33}$$

and its time derivative is

$$\dot{r}_e = (m_1 - m_2)/m_3 u_F v_F - d_3/m_3 r_F + 1/m_3\tau_{rF} - \dot{r}_F^d. \tag{34}$$

Define the CLF as

$$V_4 = 1/2 r_e^2, \tag{35}$$

then the time derivative combined with (35) and (2) is given by

$$\dot{V}_4 = r_e((m_1 - m_2)/m_3 u_F v_F - d_3/m_3 r_F + 1/m_3\tau_{rF} - \dot{r}_F^d). \tag{36}$$

Then we can choose the control law as:

$$\begin{aligned}\tau_{rF} &= m_3(-k_7 r_e - (m_1 - m_2)/m_3 u_F v_F + d_3/m_3 r_F + \dot{r}_F^d), \\ & k_7 > 0 \in \mathbb{R}.\end{aligned} \tag{37}$$

Equation (37) then becomes

$$\dot{V}_4 = -k_7 r_e^2 \le 0. \tag{38}$$

C. Switching Control under Sensor Constraints

Here we propose a switching controller design for the follower to ensure that the leader is always maintained in the sensing area of the follower's sensor. As long as the leader is in the sensing area of the follower, the backstepping controllers guarantee that the USVs converges to the desired formation. Once the leader is outside of the sensing area or approaching to the boundary of the sensing area (as shown in Fig. 3 and Fig. 4), then the follower switches to a different control law to ensure that the leader is always maintained in the sensing area of the follower.

In Fig. 4, we define

$$\alpha_1 = \alpha - K_{\text{sgn}}\varphi_F, \tag{39}$$

$$\alpha_2 = \pi/2 - \lambda_{LFi}, \tag{40}$$

where

$$K_{\text{sgn}} = \begin{cases} \text{sgn}(\alpha_2), & \alpha_2 \ne 0; \\ 1, & \alpha_2 = 0. \end{cases} \tag{41}$$

If $\|\alpha_1\| \ge \|\alpha_2\| + K_\alpha$, where K_α is the margin of the sensor constraint, the leader is moving in the sensing area of the follower, the formation will be maintained.

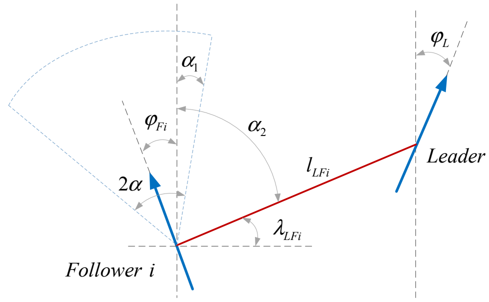

Fig. 4. Switching condition

If $\|\alpha_1\| < \|\alpha_2\| + K_\alpha$, the leader is moving outside of the sensing area or approaching to the boundary of the sensing area, which will happen under some circumstances, such as the leader slows down suddenly or the desired formation is beyond the capability of the sensor, so the switching controller should work to control the yaw angle of the follower so that the follower will keep tracking the leader, and the formation will always be maintained. The switching controller is proposed by PID method. We define

$$\Delta_{error} = K_{\text{sgn}}(\alpha_1 - \|\alpha_2\|) . \quad (42)$$

Here we should notice that if $\|\alpha_1\| < \|\alpha_2\| + K_\alpha$, the leader is approaching to the boundary of the sensing area or moving outside of the sensing area, the bearing angle λ_{LFi} may not be measured, so in (42), the value of λ_{LFi} should be chosen as the last effective bearing value which is stored in the history data. The switching control law is

$$\tau_{rFi} = K_P \Delta_{error} + K_I \int \Delta_{error} + K_D \dot{\Delta}_{error} , \quad (43)$$

where K_P, K_I and K_D are the coefficients of the switching control law.

IV. Simulation Results

To demonstrate the effectiveness of the control scheme proposed for L-F formation control of USVs with vision sensor constraints, some computer simulations are performed. Three USVs with the same parameters are chosen and modeled. The vehicles' parameters are

$$m_1 = 120 \times 10^3 \ kg , \ m_2 = 217.9 \times 10^3 \ kg ,$$

$$m_3 = 636 \times 10^5 \ kg , d_1 = 215 \times 10^2 \ kg \cdot s^{-1} ,$$

$$d_2 = 117 \times 10^3 \ kg \cdot s^{-1} , \ d_3 = 802 \times 10^4 \ kg \cdot s^{-1} ,$$

which are taken from [30]. We simulated three cases of the formation control.

For the first case, the sensor constraints are not considered, which means the switching controller is not used. The desired formation is chosen as $l_{LF1} = 5\ m$, $\lambda_{LF1} = \pi/4$, $l_{LF2} = 5\ m$, and $\lambda_{LF2} = 3\pi/4$. The initial positions of the vehicles are chosen as:

Leader: $[X_L, \ Y_L] = [0, \ 0]$,

Follower1: $[X_{F1}, \ Y_{F1}] = [-5, \ 5]$,

Follower2: $[X_{F2}, \ Y_{F2}] = [-5, \ -5]$.

And the initial velocities are chosen:

Leader: $u_L = 1\ m/s$, $v_L = 0\ m/s$, $r_L = 0.1\ rad/s$ (during the simulation time $0 \sim 30\ s$), $r_L = 0\ rad/s$ (during the simulation time $30 \sim 100\ s$), $r_L = -0.05\ rad/s$ (during the simulation time $100 \sim 200\ s$);

Follower1: $[u_{F1}, \ v_{F1}, \ r_{F1}] = [0, \ 0, \ 0]$;

Follower2: $[u_{F2}, \ v_{F2}, \ r_{F2}] = [0, \ 0, \ 0]$.

The simulation results are shown in Fig. 5 and Fig. 6. The total simulation time is 200 seconds, the leader's initial angle velocity in yaw is set to be $0.1\ rad/s$ before 30th second, and changes to $0\ rad/s$ at 30th second, then turns to $-0.05\ rad/s$ at 100th second. The surge velocity of the leader is assumed to remain unchanged during the simulation. Fig. 5 shows the formation trajectories without switching control. As one can see, the USVs achieve the desired formation successfully for both straight-line and curved-line paths. And in Fig. 6, Fig. a indicates that the distance errors in x and y directions of the two followers can converge to zero, and in Fig. b, the followers keep constant yaw angle errors with the leader from 0th to 30th second and 100th second to 200th second because of none zero yaw velocities, the yaw angle errors converge to zero from 30th to 100th second. This means that the backstepping formation control strategy works well under no sensor constraints.

However the strategy in case one can not work well in practical situation. For the second case, the practical formation control is used with sensor constraints. The desired formation is chosen as $l_{LF1} = 5\ m$, $\lambda_{LF1} = \pi/4$, $l_{LF2} = 5\ m$, and $\lambda_{LF2} = 3\pi/4$. The sensor constraint angle is set as $2\alpha = 160^\circ$. So compared with the desired formation bearing angles, we can get that the leader is kept in the sensing areas of the

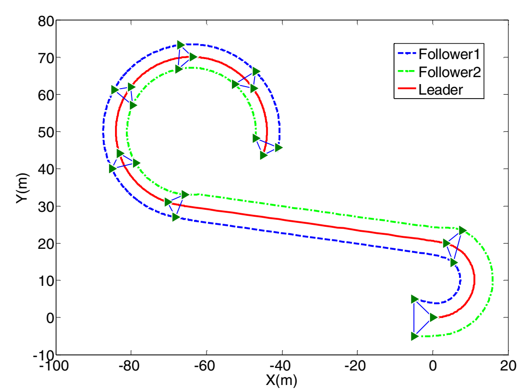

Fig. 5. Formation trajectories without sensor constraints

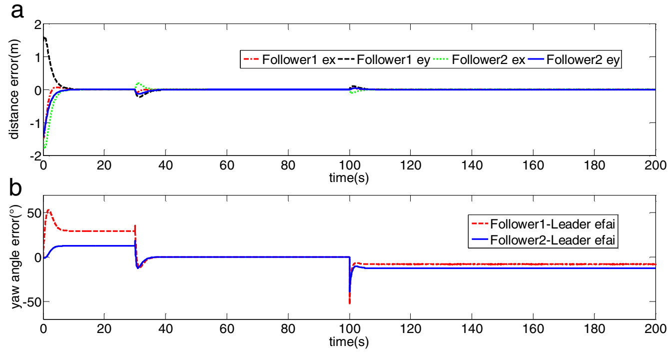

Fig. 6. Formation errors without sensor constraints

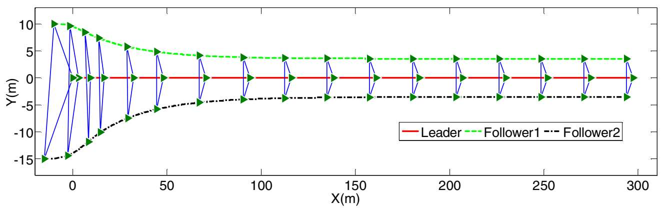

Fig. 7. Formation trajectories with sensor constraints

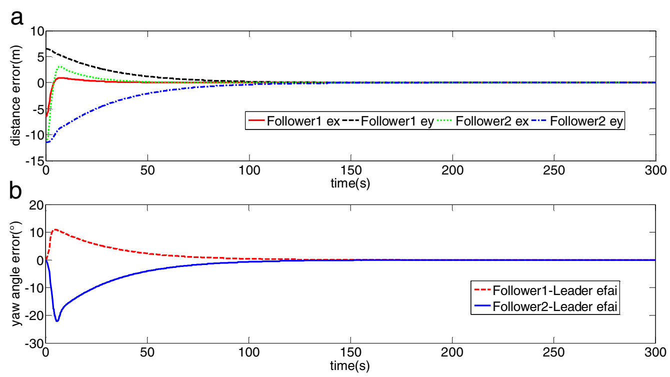

Fig. 8. Formation errors with sensor constraints

followers' sensors. The initial positions of the vehicles are chosen as:

Leader: $[X_L,\ Y_L]=[0,\ 0]$,

Follower1: $[X_{F1},\ Y_{F1}]=[-10,\ 10]$,

Follower2: $[X_{F2},\ Y_{F2}]=[-15,\ -15]$.

And the initial velocities are chosen:

Leader: $u_L=1\ m/s$, $v_L=0\ m/s$, $r_L=0\ rad/s$, the velocities maintained to be unchanged during the simulation;

Follower1: $[u_{F1},\ v_{F1},\ r_{F1}]=[0,\ 0,\ 0]$;

Follower2: $[u_{F2},\ v_{F2},\ r_{F2}]=[0,\ 0,\ 0]$.

The simulation results are shown in Fig. 7 and Fig. 8. Fig. 7 indicates that the formation is well established. And in Fig. 8, Fig. a indicates that the distance errors in x and y directions

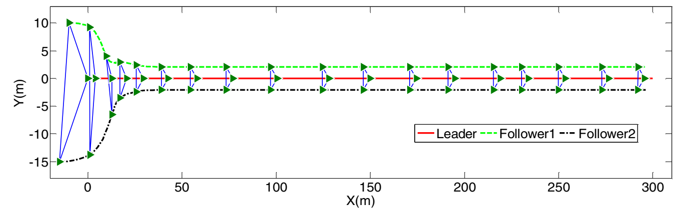

Fig. 9. Formation trajectories with sensor constraints (outside of the sensing area)

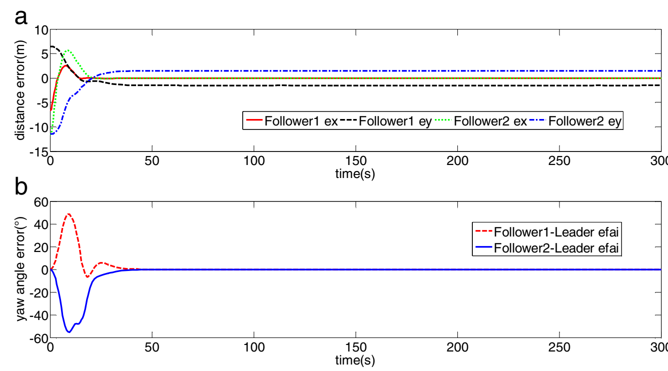

Fig. 10. Formation errors with sensor constraints (outside of the sensing area)

of the two followers converge to zero, and in Fig. b, the followers keep tracking the leader's yaw angle.

For the third case, the initial parameters of the vehicles and the desired formation are the same with the second case. However in this case, the sensor constraint angle is set as $2\alpha=60^{\circ}$. Compared with the desired formation bearing angles, we can see that the leader is outside of the sensing areas of the followers' sensors. In this case, the formation is well established as shown in Fig. 9, however, compared with the formation trajectories in Fig. 7 in the second case, the formation trajectories are smaller. In Fig. 10, though Fig. b indicates that the followers keep tracking the leader's yaw angle, however in Fig. a, the followers keep constant distance errors in x and y directions relative to the leader, which means there are constant errors in the formation control results, and the desired formation is not formed. However, the results in the third case demonstrate that the switching controller works well for keeping tracking the leader so as to the formation will always be obtained.

From the simulation results, we can see that the proposed control strategy can be used in many practical cases. For example, in one case, if the desired formation is beyond the capability of the onboard sensor, the switching controller should work to control the yaw angle of the follower so that the follower will keep tracking the leader, so the formation will also be established under our practical formation controller. In another case, if the leader slows down suddenly, the leader may be outside of the sensing area, the practical formation controller will keep the sensing being efficient and the formation will not be destroyed either.

V. CONCLUSION

In this paper, three USVs have been modeled with onboard vision sensors to perform in formation. A practical formation control strategy has been proposed for L-F formation control of the USVs which move under sensor constraints. The outer-loop part of the practical controller is designed to stabilize the formation, the efficacy of which establishing a desired formation is demonstrated by numerical simulations. And simulation results demonstrate the effectiveness of the inner-loop control scheme for achieving the desired formation and keeping the formation not being destroyed even if when the leader is outside of the sensing area. The proposed control strategy performs well in practical situations.

It should be noted that, this control method only considers triangle formations. The sensor error problems such as noise, random error and sampling rate which are inherent in the sensor are not taken in account either. For real applications, these should be considered too, and a gimbaled camera would also solve the sensor constraints problem, which will be considered in further researches.

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