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VIRTUAL-LEADER BASED FORMATION CONTROL WITH CONSTANT BEARING GUIDANCE FOR UNDERACTUATED AUVS

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Abstract. *Model complexity and control method selection directly affects the difficulty and precision of formation control. The formation control for underactuated autonomous underwater vehicle (AUV) considered in this paper consists of the target guidance for the leader and keeping the desired formation for the followers, so the virtual-leader based formation control method combined with constant bearing (CB) guidance law is proposed. The guidance part, which is based on CB guidance law, designs the heading angle and forward speed to make it asymptotically follow the target trajectory. In the formation part, a new formation control model is established by using speed coordinate transformation and virtual-leader method. The position and speed controllers are designed by combining the direct Lyapunov and backstepping theory. Simulation results demonstrate that the proposed method can control leader AUV to follow the known target path while keeping the desired formation shape with the followers.*
Keywords: Virtual-leader, Constant bearing guidance law, Formation control, Directive Lyapunov, Backstepping

1. **Introduction.** Multi-AUVs working together with a certain formation can take advantage of network communication completely to obtain the accurate and integral environment information, and efficiently complete the assigned complex tasks. As one of the research topics, formation control is studied extensively with the applications in ocean mapping, minesweeping and so on. The formation control problem for AUVs needs to consider how to keep the desired formation configuration while guiding to the target trajectory. Therefore, we study it from two levels; one is the tracking control for the followers, and the other is the guidance control for the leader AUV.

Various strategies and approaches which can be roughly categorized as behavior based, leader-following [1], virtual structure [2], and reinforcement learning [3] have been proposed for formation control. We choose to consider the virtual-leader framework which combines the advantages of virtual structure and leader-follower method in this paper. Since unlikely the reinforcement learning, it does not need too much time to learn and improve. Moreover, it can avoid the difficulty brought by complex analytical verification about the performance based on behavioral framework.

The underactuated AUV has fewer control actuators than the number of the independent directions of desired motion and in general. Therefore, compared to the precision problem caused by different control methods, the main challenges come from the structure of system model and the corresponding controller which directly affect the complexity and stability. The polar coordinate representation is usually adopted, which has the potential singularity problem. The Jacobi vector is applied to simplify and decouple system dynamic model in [4]. Serret-Frenet and Cartesian [5] coordinate representation are also applied to solve the path following problem. The cascaded and global diffeomorphism transformed approaches are applied in [6]. A controller by input-output linearization is presented in [7], but it needs to select an off-axis point in the forward direction, whereas the off-axis leads to offset, and this method is only stable locally. A globally stable but complicated sliding mode or fuzzy logic based controller is presented in [8]. In order to simplify the model structure and facilitate the latter design for controller of underactuated AUV, we use velocity coordinate transformation to establish the dynamic error model, and the control inputs are obtained by using direct lyapunov and backstepping theory to ensure the system stability.

In the aspect of guidance, generally, the line of sight (LOS) algorithm [9] is adopted which has the drawback of being susceptible to environmental disturbances, and the look-ahead distance directly impacts on the tracking precision. To overcome these shortages, helmsman behavior is introduced to improve performance in [10]. Inspired by the typical torpedo guidance trajectory design, we choose the constant bearing (CB) method due to the smallest needed normal overload.

Other than the study of formation control under the complex environment, the contribution of this paper lies in providing a new simple but clear virtual-leader based formation control combined with the CB guidance for the leader. The paper is organized as follows. In Section 2, we build the dynamic error model by velocity coordinate transformation. The control inputs are obtained by using direct Lyapunov and backstepping theory in Section 3. To ensure the normal overload minimum, the high level control is developed by employing CB guidance law for leader AUV to track the target trajectory in Section 4. Section 5 presents experimental simulations in Matlab environment to validate the performances of the proposed control algorithm. Finally, this paper ends with conclusions in Section 6.

2. **Formation System Modeling for Underactuated AUV Based on Virtual-Leader.**

2.1. Underactuated AUV model with velocity coordinate. When AUV moves in the condition of weak maneuvering, its 6-DOF model can be decoupled as horizontal and vertical movement. Neglecting the vertical motions, global inertial coordinate frame O-XY and body-fixed coordinate O-X_0Y_0 are described in Figure 1; the dynamics and kinematics models moving in the horizontal plane are established as [11]

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}_{\boldsymbol{b}}^{\boldsymbol{I}}(\boldsymbol{\psi})\boldsymbol{v} \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}\boldsymbol{v} = \boldsymbol{\tau}' \tag{2}$$

where $\boldsymbol{\eta} = \begin{bmatrix} x & y & \psi \end{bmatrix}^{\mathrm{T}}$. $\begin{bmatrix} x & y \end{bmatrix}^{\mathrm{T}}$ and ψ are the position and yaw angle of AUV in O-XY, $\boldsymbol{v} = \begin{bmatrix} u & v & r \end{bmatrix}^{\mathrm{T}}$ is defined as the velocity for surge, sway and yaw yield. $\boldsymbol{R}_{\boldsymbol{b}}^{\boldsymbol{I}}(\boldsymbol{\psi}) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is the transformation matrix,

$$\boldsymbol{C}(\boldsymbol{v}) = \begin{bmatrix} 0 & 0 & -mv + Y_{\dot{v}}v \\ 0 & 0 & mu - X_{\dot{u}}u \\ mv - Y_{\dot{v}}v & -mu + X_{\dot{u}}u & 0 \end{bmatrix},$$

$\boldsymbol{M} = diag\{m - X_{\dot{u}}, m - Y_{\dot{v}}, I_z\}$ and $\boldsymbol{D} = diag\{-X_u, -Y_v, -N_r\}$ are the carioles and centripetal terms, inertia and damping matrix respectively. $\boldsymbol{\tau}' = \begin{bmatrix} \tau_x & \tau_y & \tau_\psi \end{bmatrix}^{\mathrm{T}}$ is denoted respectively the external force in surge and sway, the external torque about the vertical.

Since the sway force of underactuated AUV is unavailable, $\tau_y = 0$. The main challenge is to eliminate the effects of the sway motion on the dynamics of $\dot{x}$ and $\dot{y}$, thus we introduce velocity coordinate O-X_1Y_1 transformation shown in Figure 1, and then the

AUV described has the nonholonomic constraint and satisfies the pure rolling without sliding movement. Equations (1) and (2) can be converted into

$$\dot{\boldsymbol{\eta}}_n = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi}_n \end{bmatrix} = \begin{bmatrix} \cos\psi_n & 0 \\ \sin\psi_n & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} U_n \\ r + \dot{\beta} \end{bmatrix} \tag{3}$$

$$\begin{gathered} \dot{U}_n = \dot{u}\cos\beta + \dot{v}\sin\beta = \frac{\tau_x + X_u u - (Y_{\dot{v}} - m)vr}{m - X_{\dot{u}}}\cos\beta + \frac{Y_v v - (M - X_{\dot{u}})uv}{m - Y_{\dot{v}}}\sin\beta \\ \dot{r} = {}^1\!/_{I_z}\left(\tau_\psi - (X_{\dot{u}} - Y_{\dot{v}})\, vu + N_r r\right) \end{gathered} \tag{4}$$

where $U_n = \sqrt{u^2 + v^2}$ is total speed, $\beta = \arctan(u/v)$ is sideslips angle, and $\psi_n = \psi + \beta$ is heading angle.

2.2. **Dynamic error model based on virtual-leader.** In the multi-AUV formation system, each independent AUV needs to know whom it should follow, and its position in the specified formation. Therefore, we define the formation parameter matrix $H_{ij} = \begin{bmatrix} i & l_{ijd} & \psi_{ijd} \end{bmatrix}^{\mathrm{T}}$, $j = 1, 2, \ldots, n$. Here i is the number of leading AUV, l_{ijd} and ψ_{ijd} are the desired relative distance and angle between the leader and follower respectively.

The virtual-leader method defines a virtual leader for every follower AUV according to the given formation, and the virtual leader not only keeps the desired relative distance and angle, but also keeps the same speed and heading angle with the leader, and its

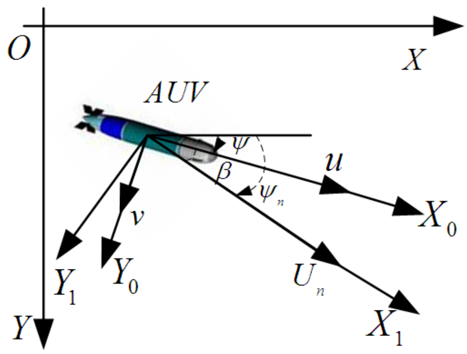

Figure 1. Coordinate frame

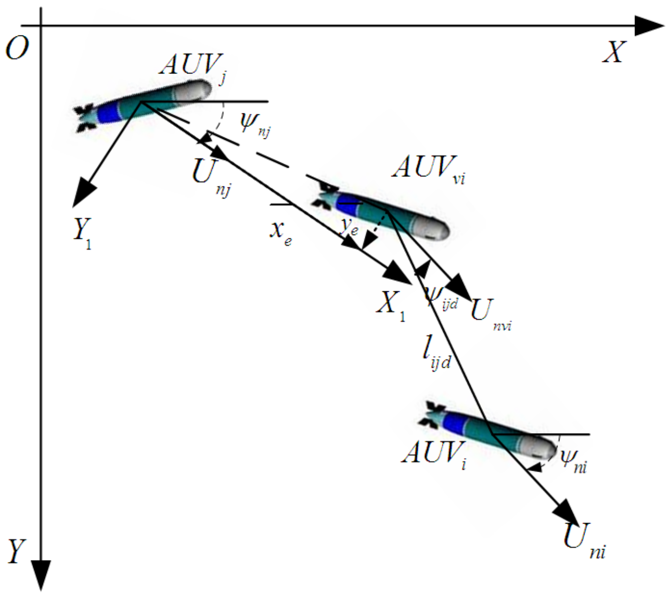

Figure 2. Virtual leader configuration of two AUVs

configuration is shown as Figure 2. Then, we can get the tracking error between the follower AUV_j and virtual leader AUV_{vi} which is denoted as

$$\boldsymbol{\eta}_{ne} = \begin{bmatrix} x_e \\ y_e \\ \psi_{ne} \end{bmatrix} = \begin{bmatrix} x_{vi} - x_j \\ y_{vi} - y_j \\ \psi_{nvi} - \psi_{nj} \end{bmatrix} = \begin{bmatrix} x_i - l_{ijd}\cos(\psi_{ni} - \psi_{ijd}) - x_j \\ y_i - l_{ijd}\sin(\psi_{ni} - \psi_{ijd}) - y_j \\ \psi_{nvi} - \psi_{nj} \end{bmatrix} \tag{5}$$

Thus, in order to design the latter controllers easily, we transform Equation (5) into the velocity coordinates $O\text{-}X_1Y_1$ of AUV_j, and the position and attitude error $\overline{\boldsymbol{\eta}_{ne}}$ are written as

$$\overline{\boldsymbol{\eta}_{ne}} = \begin{bmatrix} \overline{x_e} \\ \overline{y_e} \\ \overline{\psi_{ne}} \end{bmatrix} = \begin{bmatrix} \cos\psi_{nj} & \sin\psi_{nj} & 0 \\ -\sin\psi_{nj} & \cos\psi_{nj} & 0 \\ 0 & 0 & 1 \end{bmatrix} \boldsymbol{\eta}_{ne} \tag{6}$$

The error dynamic model can be derived as

$$\dot{\overline{\boldsymbol{\eta}_{ne}}} = \begin{bmatrix} \dot{\psi}_{nj}\overline{y_e} + U_{ni}\cos\overline{\psi_{ne}} - U_{nj} + l_{ijd}\dot{\psi}_{ni}\sin\left(\overline{\psi_{ne}} - \psi_{ijd}\right) \\ -\dot{\psi}_{nj}\overline{x_e} + U_{ni}\sin\overline{\psi_{ne}} - l_{ijd}\dot{\psi}_{ni}\cos\left(\overline{\psi_{ne}} - \psi_{ijd}\right) \\ \dot{\psi}_{ni} - \dot{\psi}_{nj} \end{bmatrix} \tag{7}$$

From Formula (7), we can find the design of $\dot{\overline{\boldsymbol{\eta}_{ne}}}$ is associated with $\begin{bmatrix} U_{nj} & \dot{\psi}_{nj} \end{bmatrix}^{\mathrm{T}}$. So one goal of formation control can be formulated to design the control input $\begin{bmatrix} U_{nj}^d & \dot{\psi}_{nj}^d \end{bmatrix}^{\mathrm{T}}$ and make the follower AUV_j from a random position achieve the position of AUV_{vi} with the given shape H_{ij}, namely $\lim\limits_{t\to\infty} \overline{\boldsymbol{\eta}_{ne}} = 0$. At the same time, in order to keep synchronized with the AUV_i, we should derive feedback control law for $\begin{bmatrix} \boldsymbol{\tau}_{xj} & \boldsymbol{\tau}_{\psi j} \end{bmatrix}^{\mathrm{T}}$ according to Equation (4), so that the speed errors tend to zero asymptotically, namely $\lim\limits_{t\to\infty} \begin{bmatrix} U_{ne} & r_e \end{bmatrix}^{\mathrm{T}} = 0$.

3. **Controller Design Based on Stepbacking and Directive Lyapunov.** With the two formation control goals addressed previously, we choose outer-loop controller $\begin{bmatrix} U_{nj}^d & \dot{\psi}_{nj}^d \end{bmatrix}^{\mathrm{T}}$ to achieve the first goal by using directive Lyapunov theory, and design the inner-loop control input $\begin{bmatrix} \boldsymbol{\tau}_{xj} & \boldsymbol{\tau}_{\psi j} \end{bmatrix}^{\mathrm{T}}$ to realize the second goal by using stepbacking method. The frame is described as the under half part of Figure 3, where Σ_j represents Formulas (1) and (2).

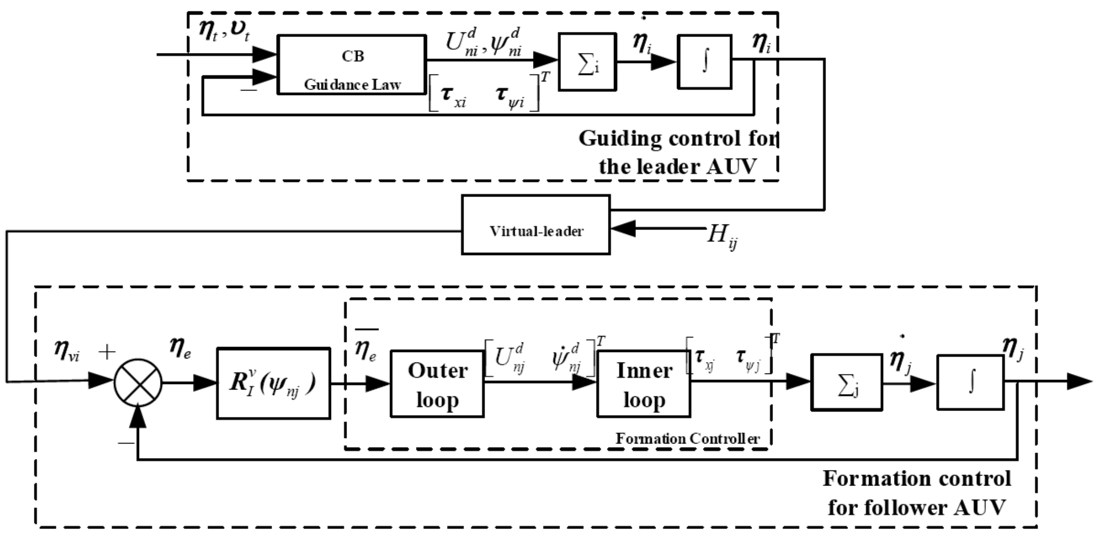

Figure 3. System frame

3.1. **Position controller design.** Choose the control inputs U_{nj}^d and $\dot{\psi}_{nj}^d$, in which, k_1, $k_2 > 0$.

$$U_{nj}^d = U_{ni}\cos\psi_{ne} + l_{ijd}\dot{\psi}_{ni}\sin(\psi_{ne} - \psi_{ijd}) + k_1\overline{x_e} \tag{8}$$

$$\begin{aligned}\dot{\psi}_{nj}^d = {} & \dot{\psi}_{ni} + \overline{y_e}U_{ni}\int_0^1 \cos(s\psi_{ne})ds + \overline{y_e}l_{ijd}\dot{\psi}_{ni}\int_0^1 \sin\left(s\psi_{ne} - \psi_{ijd}\right)ds \\ & - \overline{y_e}l_{ijd}\dot{\psi}_{ni}\cos\psi_{ijd} + k_2\psi_{ne}\end{aligned} \tag{9}$$

Proposition 3.1. *For any continuous and bounded velocity vector of leader AUV$_i$, the proposed control laws of (8) and (9) can make the system (7) stable. Namely, as $t \to \infty$, $\begin{bmatrix} \overline{x_e} & \overline{y_e} & \psi_{ne} \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}}$ is globally asymptotically stable equilibrium point.*

Proof: Select a candidate Lyapunov function as follows:

$$V_1\left(\overline{x_e}, \overline{y_e}, \overline{\psi_e}\right) = \frac{1}{2}\overline{x_e}^2 + \frac{1}{2}\overline{y_e}^2 + \frac{1}{2}\overline{\psi_{ne}}^2 \tag{10}$$

Differentiating (10) and substituting (8) and (9) into it, we get $\dot{V}_1\left(\overline{x_e}, \overline{y_e}, \overline{\psi_{ne}}\right) = -k_1\overline{x_e}^2 - k_2\overline{\psi_{ne}}^2$. For any $\overline{\boldsymbol{\eta}_e} \neq 0$, $\dot{V}_1\left(\overline{x_e}, \overline{y_e}, \overline{\psi_e}\right) < 0$, and only when $\overline{\boldsymbol{\eta}_e} = 0$, $\dot{V}_1\left(\overline{x_e}, \overline{y_e}, \overline{\psi_{ne}}\right) = 0$. According to the Lyapunov stability theorem of autonomous systems, we find that the proposed control laws in (8) and (9) can make the followers approach their virtual leader, achieve and maintain the relative distance and angle between the leader and followers as desired as well. In other words, the whole system is stable.

3.2. **Speed control law design.** Define the total speed error and yaw rate error as

$$\begin{bmatrix} U_{ne} \\ r_e \end{bmatrix} = \begin{bmatrix} U_{nj} - U_{nj}^d \\ r_j - r_j^d \end{bmatrix} \tag{11}$$

Differentiating (11) and substituting dynamics model (4) into it, we get

$$\begin{bmatrix} \dot{U}_{ne} \\ \dot{r}_e \end{bmatrix} = \begin{bmatrix} \frac{\tau_{xj} + X_u u_j - (Y_{\dot{v}} - m)v_j r_j}{m - X_{\dot{u}}}\cos\beta_j + \frac{Y_v v_j - (M - X_{\dot{u}})u_j v_j}{m - Y_{\dot{u}}}\sin\beta_j - \dot{U}_{nj}^d \\ {}^1/_{I_z}\left(\tau_\psi - (X_{\dot{u}} - Y_{\dot{v}})vu + N_r r\right) - \dot{r}_j^d \end{bmatrix} \tag{12}$$

Designing the control law $\begin{bmatrix} \tau_{xj} & \tau_{\psi j} \end{bmatrix}^{\mathrm{T}}$ for the follower as Formula (13), where k_3, $k_4 > 0$.

$$\begin{bmatrix} \tau_{xj} \\ \tau_{\psi j} \end{bmatrix} = \begin{bmatrix} \frac{(m - X_{\dot{u}})}{\cos\beta_j}\left(-k_3U_{ne} + \dot{U}_{nj}^d - \frac{Y_v v_j - (M - X_{\dot{u}})u_j v_j}{m - Y_{\dot{u}}}\sin\beta_j\right) - X_u u_j + (Y_{\dot{v}} - m)v_j r_j \\ I_z\left(-k_4 r_e + \dot{r}_j^d\right) + (X_{\dot{u}j} - Y_{\dot{v}j})v_j u_j - N_r r_j \end{bmatrix} \tag{13}$$

Proposition 3.2. *The proposed speed control laws in (13) can make the system (12) stable, namely $\lim_{t\to\infty} U_{ne} = 0$, $\lim_{t\to\infty} r_e = 0$.*

Proof: Select a candidate Lyapunov function as follows:

$$V_2(U_{ne}, r_e) = 0.5U_{ne}^2 + 0.5r_e^2 \tag{14}$$

Differentiating (14) and substituting (12) into it, we get $\dot{V}_2(U_{ne}, r_e) = -k_3U_{ne}^2 - k_4r_e^2 \leq 0$, and only when $\begin{bmatrix} U_{ne} & r_e \end{bmatrix}^{\mathrm{T}} = 0$, $\dot{V}_2(U_{ne}, r_e) = 0$, total speed and yaw rate are asymptotically stable.

4. **Guidance Law Design for Leader AUV.** Usually, when multi-AUVs are executing tasks cooperatively, the commander system should preplan the path for the leader AUV according to the task demand and current environment. So we should design the speed and heading angle controllers for the leader to navigate on the predetermined target waypoints. The guidance method is the change law of velocity vector in the process of being guided close to the target trajectory. The difference between the common classical guidance laws such as CB and PP is whether the target velocity is used as a kinematic feedfoward or not. Clearly, the PP guidance is designed for stationary target. And the LOS based motion camouflage against an object close by. Considering the smallest needed normal overload, we design the guidance law for leader based on CB method here.

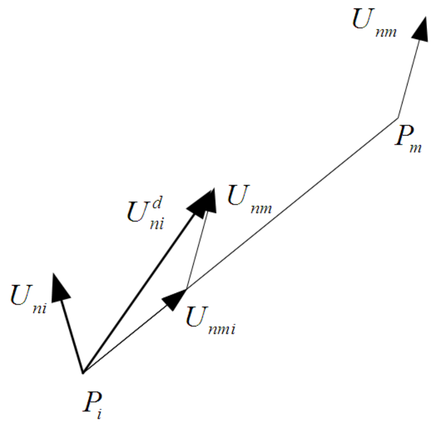

FIGURE 4. Speed vector setting by using the CB method

In CB Guidance law, the relative speed vector between the target and leader AUV is always along the sight line, this goal is equivalent to reducing the LOS rotation rate to zero such that the leader perceives the target at a constant bearing. So the speed of leader AUV$\overrightarrow{U_{ni}^d}$ can be set by target speed vector $\overrightarrow{U_{nm}}$ plusing the relative speed in the direction of sight line $\overrightarrow{U_{nmi}}$, which is shown as Figure 4.

$$\overrightarrow{U_{ni}^d} = \overrightarrow{U_{nm}} + \overrightarrow{U_{nmi}} = \overrightarrow{U_{nm}} + \kappa \overrightarrow{\tilde{P}} \Big/ \left| \overrightarrow{\tilde{P}} \right| \tag{15}$$

where, $\overrightarrow{\tilde{P}}$ is the vector of sight line from the leader AUV_i to target, $\overrightarrow{\tilde{P}} = \overrightarrow{P_m} - \overrightarrow{P_i}$, the length of $\overrightarrow{\tilde{P}}$ is $\left| \overrightarrow{\tilde{P}} \right| = \sqrt{\overrightarrow{\tilde{P}}^{\mathrm{T}} \overrightarrow{\tilde{P}}} \geq 0$. We can choose the parameter

$$\kappa = U_{a,\max} \left| \overrightarrow{\tilde{P}} \right| \Big/ \sqrt{\overrightarrow{\tilde{P}}^{\mathrm{T}} \overrightarrow{\tilde{P}} + \Delta_P^2}, \quad \kappa \geq 0,$$

and the maximum speed compared with target speed is defined as $U_{a,\max} = \varsigma U_t$, $0 < \varsigma < 1$ to reduce the speed of AUV_i rather than turning 180° when AUV_i has surpassed the target and $\Delta_P > 0$ describes the process when AUV_i close to the target, which directly reflects the tracking character.

The sway velocity cannot be directly controlled for underactuated AUV. Thus, the control for speed vector can be decoupled into forward speed control and angular rate control. The control input $\left[\begin{array}{cc} \tau_{xi} & \tau_{\psi i} \end{array} \right]^{\mathrm{T}}$ is designed in the same way introduced in Section 3.2, and its control structure is shown in the upper half of Figure 3.

5. **Simulation.** To illustrate the performance of developed new model, guidance law and controller for undercatuated AUVs, we simulate the motion of three AUVs.

$$\left[\begin{array}{cc} 30 + 0.6t\cos\left(\pi/30 + 0.0003t\right) & 50 + 0.6t\sin\left(\pi/30 + 0.0003t\right) \end{array} \right]^{\mathrm{T}}$$

is the defined target trajectory. Initial positions, yaw angles and the surge velocity, sway velocity and yaw rate are $\eta_{10} = \begin{bmatrix} 0 & 0 & \pi/7 \end{bmatrix}^{\mathrm{T}}$, $\eta_{20} = \begin{bmatrix} -1 & 0 & 40 & \pi/5 \end{bmatrix}^{\mathrm{T}}$, $\eta_{30} = \begin{bmatrix} 20 & -10 & \pi/5 \end{bmatrix}^{\mathrm{T}}$, $\upsilon_{10} = \upsilon_{20} = \upsilon_{30} = \begin{bmatrix} 2 & 0.1 & 0.1 \end{bmatrix}^{\mathrm{T}}$ respectively. Desired formation parameter can be described as $H_{12} = \begin{bmatrix} 1 & 10 & \pi/3 \end{bmatrix}^{\mathrm{T}}$, $H_{13} = \begin{bmatrix} 1 & 10 & -\pi/3 \end{bmatrix}^{\mathrm{T}}$. Dynamics parameters and control parameters are adopted as Table 1.

TABLE 1. Dynamics and control parameters

dynamics parameters		control parameters	
m	125kg	k_1	0.1
$X_u = Y_v$	-100	k_2	0.01
$X_{\dot{u}} = Y_{\dot{v}}$	-62.5	k_3	0.05
N_r	300	k_4	0.8
I_z	8Nms^2	ς	0.8

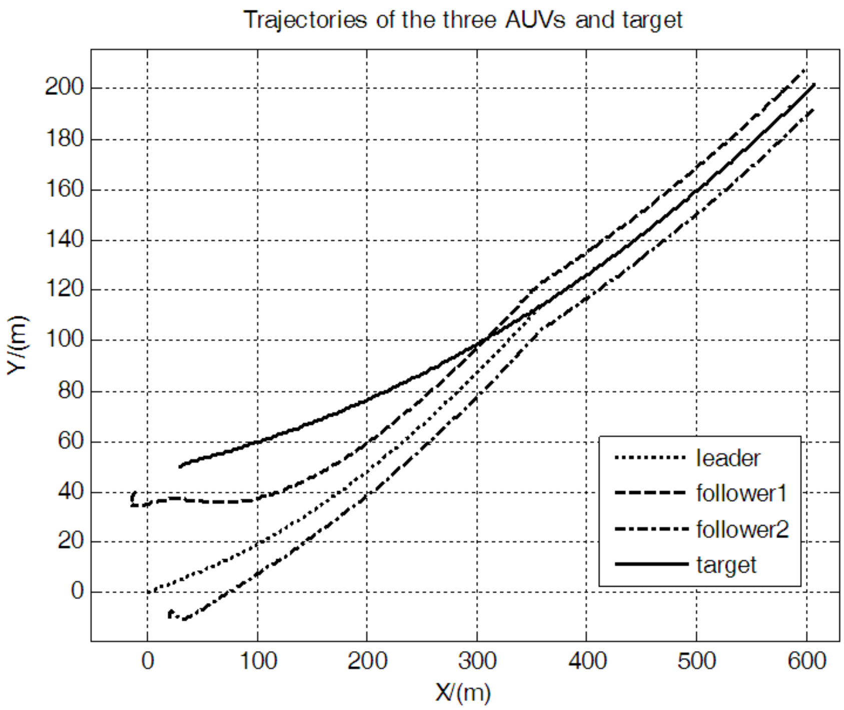

FIGURE 5. Trajectories of the leader, followers and target

The trajectories of three AUVs and target are shown in Figure 5. It can be observed that leader can eventually keep up with the target while the followers form and keep the desired equilateral triangle geometric shape with the leader successfully. Further, in order to analyze the following precision, the tracking errors are given in Figure 6. The relative distance between the leader and target is gradually approaching 0, while the relative distance between the followers and leader represented by l_{12} and l_{13} are gradually approaching 10m which is the desired value. Figure 7 verifies that the velocity vector of followers can keep consistent and converge to the leader. Apparently, the formation control method proposed in this paper is feasible and correct, and system can be stable quickly.

6. **Conclusions.** In this paper, a simple but effective virtual-leader based formation control with constant bearing guidance for underactuated AUVs is presented. Based on the virtual-leader construction, the tracking error model in the velocity coordination frame

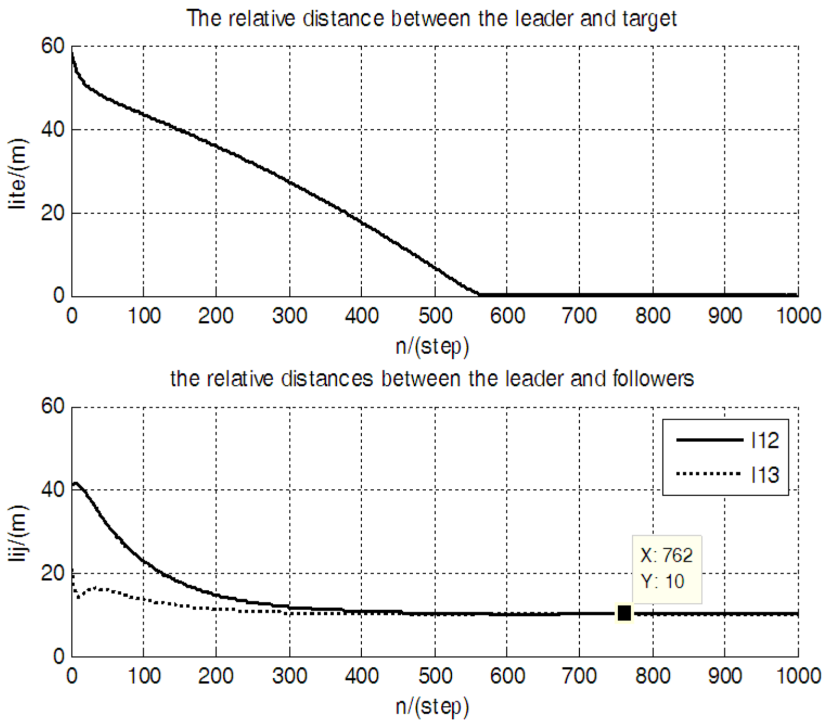

FIGURE 6. Tracking errors

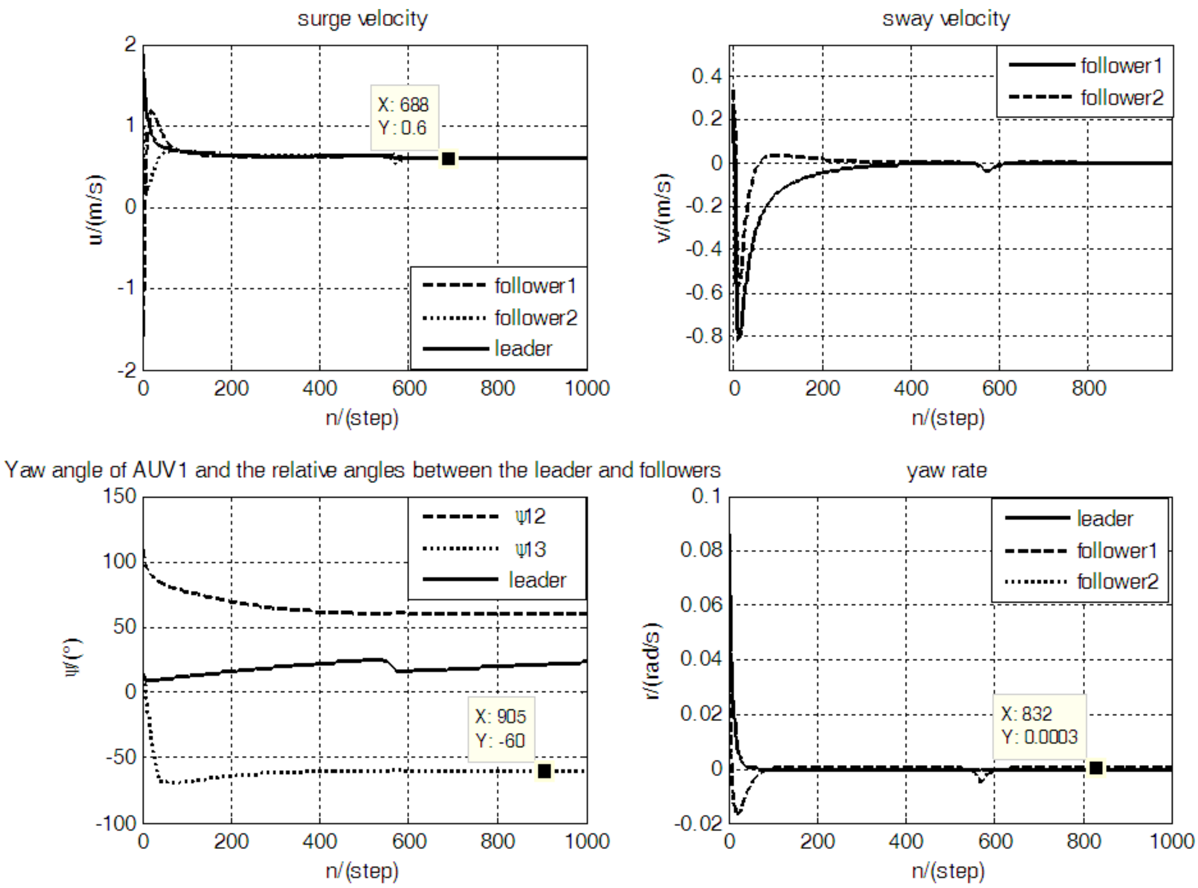

FIGURE 7. Velocity of the followers

is established, and the controllers are designed by direct Lyapunov and backstepping as well. Moreover, the guidance law based on CB for leader tracking the target trajectory is proposed. The simulation results have demonstrated the effectiveness. Further research will focus on handling uncertainties and time delayed formation control of AUVs.

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