

# Multi-level DVS Guidance and Output-feedback Path-following Control for Marine Surface Vehicles

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**Abstract** : This paper deals with the path-following control for marine surface vehicles with underactuated characteristics. In consideration of practical limitations of actuators, an improved DVS(dynamic virtual ship) guidance algorithm is proposed with the multi-level DVS optionally selected to be tracked. To address the output-feedback control issue, an adaptive FLS(fuzzy logical systems) is devised to online approximate the kinematic states. Based on that observing framework, the path-following control law is thereafter derived. Simulations testify effectiveness of the proposed scheme.

**Key words** : Path Following Control, Underactuated Ships, Multi-level DVS Guidance, Adaptive FLS Observer

**Background**

- Tradition guidance approach for path-following control such as LOS guidance and SF frame an not be easily integrated with advanced cybernetics.
- There exists unbalance development between control theories and nautical practice.

**Objective of this research**

- Developing a path-following control law for underactuated marine surface vehicles with respect to two degrees of freedom i.e. Yawing and surging.
- Taking into account practical factors in ship's motion control, such as limitation of actuators and possible failure of sensors.

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**Contributions of this research**

- Multi-level DVS(dynamic virtual ship) guidance → Solve → Saturation of actuators
- Adaptive FLS observer for kinematic states → Solve → Inaccuracy and possible failure of sensors
- DSC(dynamic surface control) first-order filter → Solve → Explosion of complexity of direct differentiation

**Thought of design**

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**Mathematic model**

**Kinematic loop**

$$\begin{cases} \dot{x} = u \cos \psi - v \sin \psi \\ \dot{y} = u \sin \psi + v \cos \psi \\ \dot{\psi} = r \end{cases}$$

**Dynamic loop**

$$\begin{cases} \dot{u} = \frac{m_v}{m_u} vr - \frac{d_u}{m_u} v + \frac{\tau_u}{m_u} \\ \dot{v} = -\frac{m_u}{m_v} ur - \frac{d_v}{m_v} v \\ \dot{r} = \frac{m_u - m_v}{m_r} uv - \frac{d_r}{m_r} r + \frac{\tau_r}{m_r} \end{cases}$$

As for path-following control issue, only three degrees of freedom are considered, seeing the figure. The kinematic loop denotes the attitude of ship in earth frame. The dynamic loop implies the motion states in body frame.

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**Introduction of DVS**

**Advantages**

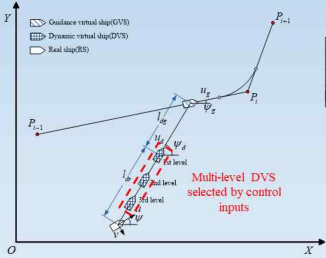
- The guidance derives the reference command of surging and yawing speed, easily to combined with cybernetics.
- The turning maneuvering for turning nearby waypoints is also under control.
- The DVS performs as the buffer between GVS and RS, the limitation of actuators is considered.

In DVS guidance, the GVS is used to generate the smooth reference path; the DVS is used as the buffer between RS and GVS for directly tracking by RS.

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### Multi-level DVS guidance



### Error system via coordinate transformation

$$\begin{bmatrix} x_e \\ y_e \\ \psi_e \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_d - x \\ y_d - y \\ \psi_d - \psi \end{bmatrix}$$

$$\begin{cases} \dot{x}_e = -u + u_d \cos\psi_e + r y_e \\ \dot{y}_e = -v + u_d \sin\psi_e - r x_e \\ \dot{\psi}_e = -r + r_d \end{cases}$$

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### Adaptive FLS observer design

Fuzzy logic system is adopted to approximate the uncertainties of models.

$$\begin{cases} \dot{\hat{x}} = \hat{u} \cos\psi - \hat{v} \sin\psi + l_1 \hat{x} \cos\psi - l_1 \hat{y} \sin\psi \\ \dot{\hat{y}} = \hat{u} \sin\psi + \hat{v} \cos\psi + l_1 \hat{x} \sin\psi + l_1 \hat{y} \cos\psi \\ \dot{\hat{\psi}} = \hat{r} + l_2 \hat{\psi} \\ \dot{z}_1 = \hat{W}_1^T \phi_1 + \frac{r_e}{m_e} + (l_1 l_1 + 1) \hat{x} - x_e + l_2 u_e \\ \dot{z}_2 = \hat{W}_2^T \phi_2 + (l_1 l_1 + 1) \hat{y} - y_e \\ \dot{z}_3 = \hat{W}_3^T \phi_3 + \frac{r_e}{m_e} + (l_1 l_1 + 1) \hat{\psi} - \psi_e + l_2 r_e \\ \hat{u} = z_1 + l_2 \hat{x}, \quad \hat{v} = z_2 + l_2 \hat{y}, \quad \hat{r} = z_3 + l_2 \hat{\psi} \end{cases}$$

Singleton fuzzification; Product inference; Center average defuzzification

$$\begin{cases} W_1^T \phi_1(\hat{u}, \hat{v}, \hat{r}, \hat{y}) = \frac{m_u}{m_e} v r - \frac{d_u}{m_e} u - l_2 r \hat{y} \\ W_2^T \phi_2(\hat{u}, \hat{v}, \hat{r}, \hat{x}) = -\frac{m_u}{m_e} u r - \frac{d_v}{m_e} v + l_2 r \hat{x} \\ W_3^T \phi_3(\hat{u}, \hat{v}, \hat{r}) = \frac{m_u}{m_e} u v - \frac{d_r}{m_e} r \end{cases}$$

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### Virtual controllaws

$$\begin{cases} \alpha_u = k_x x_e + u_d \cos\psi_e \\ \alpha_v = \arcsin\left(\frac{\hat{y} - k_y y_e}{u_d}\right) \\ \alpha_r = k_\psi \hat{\psi}_e + r_d - \dot{\beta}_v \end{cases}$$

Difficult to acquire  
 $\alpha_u, \alpha_v, \alpha_r$

### DSC first-order filter

$$\begin{cases} T_u \dot{\beta}_u + \beta_u = \alpha_u + T_u x_e \\ T_v \dot{\beta}_v + \beta_v = \alpha_v \\ T_r \dot{\beta}_r + \beta_r = \alpha_r + T_r \hat{\psi}_e \end{cases}$$

### Direct control laws

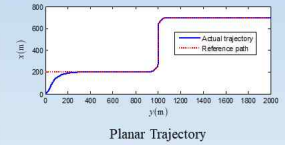
$$\begin{cases} \tau_u = m_u (-\hat{W}_1^T \phi_1 - \tilde{x} + 2x_e + \dot{\beta}_u - k_x u_e) \\ \tau_r = m_r (-\hat{W}_3^T \phi_3 - \tilde{\psi} + 2\hat{\psi}_e + \dot{\beta}_r - k_r r_e) \end{cases}$$

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### Experimental objective



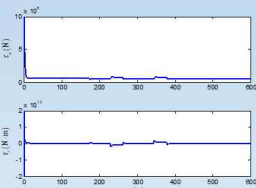
### Experimental results



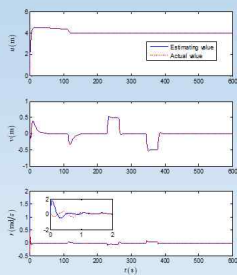
$$\begin{aligned} m_u &= 6.0806 \times 10^4; m_v = 1.0592 \times 10^5; m_r = 7.1035 \times 10^3; \\ d_u &= 4 \times 10^4; d_v = 2 \times 10^6; d_r = 2 \times 10^{10} \end{aligned}$$

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### Experimental results



Direct control inputs



Observation results

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### Conclusion

- The proposed multi-level DVS guidance could further reduce the saturation limitation of actuators.
- The introduction of adaptive FLS observer could replace the function of sensors and controller is structured on the frame of FLS observer.
- The introduction of DSC filter solve the problem of explosion of complexity.

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