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极坐标系下的欠驱动无人艇分块反步镇定控制

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摘 要:针对非对称欠驱动无人艇的镇定控制问题,提出了基于极坐标系的一类多输入多输出分块反步法,设计了一种漂角极坐标系作为艇体的动坐标系,以极坐标系代替直角坐标系作为大地坐标系,将漂角、艏向角与极角融合处理,获得了极坐标系下无人艇水平面运动的运动学和动力学方程,使直角坐标系下的欠驱动问题简化为极坐标系下的全驱动问题。结合李亚普诺夫稳定性理论和反步法设计了一种极坐标系下的多输入多输出分块反步镇定控制律,实现了非对称欠驱动无人艇的镇定控制。在实验室半物理仿真平台下,以某长度为 1.2 m、质量为 17.5 kg 的无人艇模型为实例进行镇定控制仿真试验,对比分析了分块反步镇定控制算法与传统基于对称模型的反步控制算法的控制结果。分析结果表明:分块反步镇定控制算法的位姿收敛速度提高了约 10 s,位置和艏向角镇定误差分别降低了约 0.3 m 和 10°,线速度和角速度超调量分别降低了约 0.6 $\mathrm{m\cdot s^{-1}}$ 和 2 $\mathrm{rad\cdot s^{-1}}$,因此,基于非对称模型的极坐标系下欠驱动分块反步法具有较大的可靠性、稳定性和精确性。

关键词:船舶工程;非对称无人艇;欠驱动控制;极坐标系;多输入多输出;分块反步法;李亚普诺夫稳定性理论

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Block backstepping stabilization control of underactuated USV in polar coordinate system

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Abstract: To the stabilization problem of underactuated unsymmetrical unmanned surface vessel (USV), a block backstepping approach with multiple inputs and multiple outputs (MIMO) was proposed in polar coordinate system. A drift angle polar coordinate system was designed as body-fixed moving coordinate system, and Cartesian coordinate system was replaced by polar coordinate system as earth-fixed coordinate system. By combining the drift angle, yaw angle and polar angle, the kinematics and dynamics equations of USV horizontal plane motion in polar coordinate system were obtained, so that the underactuated problem in Cartesian coordinate systems was simplified to the full actuated problem in polar coordinate system. Based on Lyapunov stability theory and the backstepping approach, MIMO block backstepping stabilization control laws for underactuated unsymmetrical USV in polar coordinate system was designed. With the aid of semi-physical simulation platform in the laboratory, an USV model with 1.2 m and 17.5 kg was taken for stabilization control simulation experiment. The proposed block backstepping stabilization control algorithm was compared with the traditional backstepping

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control algorithm based on symmetry model. Comparison result shows that the convergence rates of position and yaw attitude increase by about 10 s, the stabilization errors of position and yaw angle decrease by about 0.3 m and 10° respectively, the overshoots of linear velocity and yaw angle velocity reduce by about 0.6 m·s^{-1} and 2 rad·s^{-1} separately, so the proposed backstepping control method has higher reliability, stability and accuracy. 3 tabs, 10 figs, 25 refs.

Key words: ship engineering; unsymmetrical USV; underactuated control; polar coordinate system; MIMO; block backstepping approach; Lyapunov stability theory

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0 引 言

水面无人艇(Unmanned Surface Vessel, USV)是能在广阔海洋中自主航行,并完成指定任务的一类水面无人航行器,由于在情报搜集、侦查、扫雷、反潜、搜救与水文地理勘察等方面应用前景广泛,而倍受世界各国研究人员的关注[1-3]。无人艇的运动控制系统是完成各项任务的重要保障,而镇定控制系统是运动控制系统的最基本控制单元[4-5],已经有一些学者研究了无人艇/船舶的镇定控制问题。

针对常规基于对称船舶模型的镇定控制问题,Chommam 等借助微分同胚变换设计了一类非连续控制律,实现了船舶的渐近镇定控制[6-7];Liu 等基于传统单输入单输出(Single Input Single Output, SISO)反步法、级联系统理论和李亚普诺夫稳定性理论,得到了欠驱动船舶的镇定控制律[8-9];李晔等基于李亚普诺夫稳定性理论、滑模方法与切换控制技术等研究了船舶镇定控制问题[10-14]。针对基于非对称船舶(左右对称,前后不对称船舶)模型的镇定控制问题,Yuan 等通过直角坐标变换和状态反馈变换,利用反步法和级联系统理论得到了 K 指数镇定控制律[15];Zhang 等基于切换控制技术实现了非对称船舶的渐近镇定控制[16];Ma 等利用级联系统理论、反步法与李亚普诺夫稳定性理论等实现了非对称船舶的全局一致渐近点镇定控制[17-19]。

在上述研究中,Liu 等为了简化处理,忽略不对称性因素,使得船舶控制系统的系数矩阵非对角元素不存在非零项[8-14],虽简化了控制器设计过程,但由于实际船舶模型均为前后不对称,忽略不对称性将导致系统的控制精度降低;Yuan 等讨论了考虑不对称性因素的必要性等问题,但并没有阐述和论证针对忽略不对称性因素而造成的具体控制系统性能差别[15-19]。此外,由于基于分块反步法的控制器设计过程简单与稳定性优越,在飞行器设计与陆地机器人等领域应用较广泛,而在海洋运载器方面还没有学者展开研究。Robinson 研究了分块反步法在飞行器飞行控制当中的应用[20];Chang 研究了分块反步法在多输入多输出(Multiple Input Multiple Output, MIMO)非线性系统轨迹跟踪控制中的应用[21];Rudra 等研究了分块反步法在欠驱动连杆机器人控制系统中的应用[22];Do 基于反步法研究了非完整系统的镇定控制问题[23]。

本文基于以上研究成果,考虑了船舶模型非对称性因素,为了阐述与论证控制性能差别与分块反步方法在船舶运动控制领域的广泛应用,提出了一种极坐标系下 MIMO 分块反步法,用于欠驱动无人艇的镇定控制,并论述了模型非对称性造成的控制性能差别。

1 无人艇运动模型

无人艇在纵荡、横荡和艏摇 3 个方向的运动学和动力学模型[24]分别为

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}\boldsymbol{\upsilon} \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{\upsilon}} + \boldsymbol{C}\boldsymbol{\upsilon} + \boldsymbol{D}\boldsymbol{\upsilon} = \boldsymbol{\tau} \tag{2}$$

$$\boldsymbol{\eta} = (x, y, \psi)^{\mathrm{T}}$$

$$\boldsymbol{\upsilon} = (u, v, r)^{\mathrm{T}}$$

$$\boldsymbol{R} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{M} = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix}$$

$$\boldsymbol{C} = \begin{bmatrix} 0 & 0 & c_{13} \\ 0 & 0 & c_{23} \\ c_{31} & c_{32} & 0 \end{bmatrix}$$

$$\boldsymbol{D}=\begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix}$$

$$\boldsymbol{\tau}=(F,0,T)^{\mathrm{T}}$$

$$c_{13}=-c_{31}=-m_{22}v-\frac{1}{2}(m_{23}+m_{32})r$$

$$c_{23}=-c_{32}=m_{11}u$$

式中：$\boldsymbol{\eta}$ 为无人艇位姿；x、y 分别为无人艇在惯性坐标系下纵向、横向的位置；ψ 为艏向角；$\boldsymbol{v}$ 为速度向量；u 为纵荡速度；v 为横荡速度；r 为艏摇角速度；$\boldsymbol{R}$ 为艏摇的旋转矩阵；$\boldsymbol{M}$ 为惯性系数矩阵（包含附加质量系数项）；m_{11}、m_{22}、m_{33} 分别为 u、v、r 方向的惯性系数（包含附加质量系数）；m_{23}、m_{32} 分别为 v 在 r 方向、r 在 v 方向的惯性系数（包含附加质量系数项），且 m_{23} 与 m_{32} 相等；$\boldsymbol{C}$ 为科氏矩阵；$\boldsymbol{D}$ 为阻尼系数矩阵；d_{11}、d_{22}、d_{33} 分别为 u、v、r 方向的阻尼系数；d_{23}、d_{32} 分别为 v 在 r 方向、r 在 v 方向的阻尼系数；$\boldsymbol{\tau}$ 为控制力向量；F 为推进器提供的纵向控制力；T 为船舵提供的控制力矩。

2　控制器设计

2.1　模型变换

为了解决由无人艇非对称性带来的惯性系数矩阵与阻尼系数矩阵非对角线元素存在非零项的问题，定义

$$\begin{cases} X=x+\dfrac{m_{23}}{m_{22}}[\cos(\psi)-1] \\ Y=y+\dfrac{m_{23}}{m_{22}}\sin(\psi) \\ \Phi=\psi \\ U=u \\ V=v+\dfrac{m_{23}}{m_{22}}r \\ R=r \end{cases} \tag{3}$$

则无人艇的运动学模型式(1)和动力学模型式(2)可合并为

$$\begin{cases} \dot{X}=U\cos(\Phi)-V\sin(\Phi) \\ \dot{Y}=U\sin(\Phi)+V\cos(\Phi) \\ \dot{\Phi}=R \\ \dot{U}=\dfrac{m_{22}}{m_{11}}VR-\dfrac{d_{11}}{m_{11}}U+\dfrac{1}{m_{11}}F \\ \dot{V}=-\dfrac{m_{11}}{m_{22}}UR-\dfrac{d_{22}}{m_{22}}V+\dfrac{d_{22}m_{23}-d_{23}m_{22}}{m_{22}^2}R \\ \dot{R}=\dfrac{(m_{11}-m_{22})m_{22}}{m_{22}m_{33}-m_{23}^2}UV+\dfrac{d_{22}m_{23}-d_{32}m_{22}}{m_{22}m_{33}-m_{23}^2}V- \\ \quad \dfrac{d_{22}m_{23}^2-d_{23}m_{22}m_{23}-d_{32}m_{22}m_{23}+d_{33}m_{22}^2}{m_{22}(m_{22}m_{33}-m_{23}^2)}R+ \\ \quad \dfrac{m_{22}}{m_{22}m_{33}-m_{23}^2}T \end{cases} \tag{4}$$

式中：X、Y、Φ 为变换后无人艇的对应位姿；U、V、R 分别为变换后的对应速度。

2.2　极坐标系下模型建立

如图 1 所示，建立极坐标系(ρ,θ)，ρ 为极径，θ 为极角；船舶惯性参考坐标系为 xOy，O 为坐标原点；$x_bO_by_b$ 为船舶随体坐标系，O_b 为坐标原点，取为船舶重心，x_b、y_b 分别为船舶运动的纵向与横向；ω 为船舶运动合速度 v_c 与极径 ρ 的夹角。

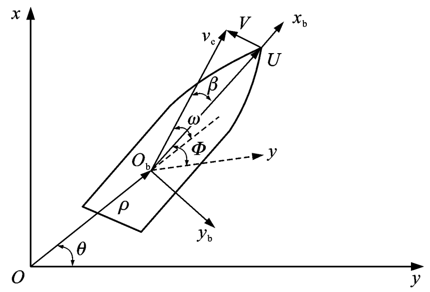

图 1　坐标关系

Fig. 1　Coordinate relations

在极坐标系中，以(ρ,θ,Φ)代替(X,Y,Φ)表示船舶的位姿，以(v_c,β,R)代替(U,V,R)表示船舶的速度，β 为漂角，且有

$$\rho=\sqrt{X^2+Y^2}$$

$$v_c=\sqrt{U^2+V^2}$$

$$\theta=\arctan\left(\frac{Y}{X}\right)$$

$$\beta=\arctan\left(\frac{V}{U}\right)$$

定义当 ρ 为 0 时，θ、$\dot{\theta}$、$\ddot{\theta}$ 均为 0，当 v_c 为 0 时，β、$\dot{\beta}$、$\ddot{\beta}$ 均为 0，则有

$$\begin{cases} \dot{\rho}=v_c\cos(\omega) \\ \dot{\omega}=r_\omega \\ \dot{v}_c=-\dfrac{m_{11}}{m_{22}}UR\sin(\beta)-\dfrac{d_{22}}{m_{22}}V\sin(\beta)+ \\ \quad \dfrac{d_{22}m_{23}-d_{23}m_{22}}{m_{22}^2}R\sin(\beta)+\left(\dfrac{m_{22}}{m_{11}}VR- \right. \\ \quad \left.\dfrac{d_{11}}{m_{11}}U\right)\cos(\beta)+\dfrac{1}{m_{11}}F\cos(\beta) \\ \dot{r}_\omega=\dfrac{(m_{11}-m_{22})m_{22}}{m_{22}m_{33}-m_{23}^2}UV+\dfrac{d_{22}m_{23}-d_{32}m_{22}}{m_{22}m_{33}-m_{23}^2}V- \\ \quad \dfrac{d_{22}m_{23}^2-d_{23}m_{22}m_{23}-d_{32}m_{22}m_{23}+d_{33}m_{22}^2}{m_{22}(m_{22}m_{33}-m_{23}^2)}R+ \\ \quad \ddot{\beta}-\ddot{\theta}+\dfrac{m_{22}}{m_{22}m_{33}-m_{23}^2}T \end{cases} \tag{5}$$

$$\omega=\Phi+\beta-\theta$$

$$r_\omega = R + \dot{\beta} - \dot{\theta}$$

$$\dot{\beta} = \frac{u\dot{v} - v\dot{u}}{v_c^2}$$

$$\dot{\theta} = \frac{v_c}{\rho}\sin(\omega)$$

$$\ddot{\beta} = \frac{1}{v_c^2}(u\ddot{v} - \ddot{u}v) - 2\frac{\dot{v}_c}{v_c}\dot{\beta}$$

$$\ddot{\theta} = \frac{\dot{v}_c}{\rho}\sin(\omega) + \frac{v_c r_\omega}{\rho}\cos(\omega) - \frac{\dot{\rho}v_c}{\rho^2}\sin(\omega) = \frac{\dot{v}_c}{\rho}\sin(\omega) + \frac{v_c r_\omega}{\rho}\cos(\omega) - \frac{v_c^2}{\rho^2}\sin(\omega)\cos(\omega)$$

式中：r_ω 为与角 ω 对应的角速度。

由式(5)可设计

$$a_v = -\frac{m_{11}}{m_{22}}UR\sin(\beta) - \frac{d_{22}}{m_{22}}V\sin(\beta) + \frac{d_{22}m_{23} - d_{23}m_{22}}{m_{22}^2}R\sin(\beta) + \left(\frac{m_{22}}{m_{11}}VR - \frac{d_{11}}{m_{11}}U\right)\cos(\beta)$$

$$a_r = \frac{(m_{11} - m_{22})m_{22}}{m_{22}m_{33} - m_{23}^2}UV + \frac{d_{22}m_{23} - d_{32}m_{22}}{m_{22}m_{33} - m_{23}^2}V - \frac{d_{22}m_{23}^2 - d_{23}m_{22}m_{23} - d_{32}m_{22}m_{23} + d_{33}m_{22}^2}{m_{22}(m_{22}m_{33} - m_{23}^2)}R + \ddot{\beta} - \ddot{\theta}$$

$$u_1 = \frac{1}{m_{11}}F\cos(\beta)$$

$$u_2 = \frac{m_{22}}{m_{22}m_{33} - m_{23}^2}T$$

则系统式(5)可写成

$$\begin{cases} \dot{\rho} = v_c\cos(\omega) \\ \dot{\omega} = r_\omega \\ \dot{v}_c = a_v + u_1 \\ \dot{r}_\omega = a_r + u_2 \end{cases} \tag{6}$$

2.3 控制器设计

定义

$$\begin{cases} \boldsymbol{\chi} = (\rho, \omega)^{\mathrm{T}} \\ \boldsymbol{\zeta} = (v_c, r_\omega)^{\mathrm{T}} \\ \boldsymbol{u} = (u_1, u_2)^{\mathrm{T}} \end{cases}$$

则系统式(6)可以改写成

$$\begin{cases} \dot{\boldsymbol{\chi}} = \boldsymbol{B}(\boldsymbol{\chi})\boldsymbol{\zeta} \\ \dot{\boldsymbol{\zeta}} = \boldsymbol{A}(\boldsymbol{\chi}, \boldsymbol{\zeta}) + \boldsymbol{u} \end{cases} \tag{7}$$

且

$$\begin{cases} \boldsymbol{B}(\boldsymbol{\chi}) = \mathrm{diag}[\cos(\omega), 1] \\ \boldsymbol{A}(\boldsymbol{\chi}, \boldsymbol{\zeta}) = (a_v, a_r)^{\mathrm{T}} \end{cases}$$

设计 $\boldsymbol{\zeta}$ 的虚拟输入 $\boldsymbol{\alpha}_\zeta$ 为

$$\boldsymbol{\alpha}_\zeta = (-k_1\rho\cos(\omega), -k_2\omega)^{\mathrm{T}}$$

控制参数 $k_1 > 0, k_2 > 0$，且有 $\boldsymbol{\alpha}_\zeta$ 的初值 $\boldsymbol{\alpha}_\zeta(\mathbf{0})$ 为 $\mathbf{0}$。令

$$V_1 = \frac{1}{2}\boldsymbol{\chi}^{\mathrm{T}}\boldsymbol{\chi}$$

选取系统式(7)的李亚普诺夫函数为

$$V_2 = V_1 + \frac{1}{2}(\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta)^{\mathrm{T}}(\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta)$$

对李亚普诺夫函数求导可得

$$\dot{V}_2 = \frac{\partial V_1}{\partial \boldsymbol{\chi}}\boldsymbol{B}(\boldsymbol{\chi})\boldsymbol{\alpha}_\zeta + \frac{\partial V_1}{\partial \boldsymbol{\chi}}\boldsymbol{B}(\boldsymbol{\chi})(\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta) + (\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta)^{\mathrm{T}}\left[\boldsymbol{A}(\boldsymbol{\chi}, \boldsymbol{\zeta}) + \boldsymbol{u} - \frac{\partial \boldsymbol{\alpha}_\zeta}{\partial \boldsymbol{\chi}}\boldsymbol{B}(\boldsymbol{\chi})\boldsymbol{\zeta}\right] \tag{8}$$

取

$$\boldsymbol{u} = \frac{\partial \boldsymbol{\alpha}_\zeta}{\partial \boldsymbol{\chi}}\boldsymbol{B}(\boldsymbol{\chi})\boldsymbol{\zeta} - \left[\frac{\partial V_1}{\partial \boldsymbol{\chi}}\boldsymbol{B}(\boldsymbol{\chi})\right]^{\mathrm{T}} - \boldsymbol{A}(\boldsymbol{\chi}, \boldsymbol{\zeta}) - \boldsymbol{K}(\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta) \tag{9}$$

$$\boldsymbol{K} = \mathrm{diag}(k_3, k_4) \quad k_3 > 0, k_4 > 0$$

式中：k_3、k_4 为控制参数。

展开式(9)可得

$$\boldsymbol{u} = (u_1, u_2)^{\mathrm{T}} = (-k_1v_c\cos^2(\omega) + k_1\rho r_\omega\sin(\omega) + \rho\cos(\omega) - a_v - k_3v_c - k_1k_3\rho\cos(\omega), \omega - k_2r_\omega - a_r - k_4r_\omega - k_2k_4\omega)^{\mathrm{T}} = ((-k_3 - k_1\cos^2(\omega))v_c + k_1\rho r_\omega\sin(\omega) + (-k_1k_3 + 1)\rho\cos(\omega) - a_v, (-k_4 - k_2)r_\omega + (-k_2k_4 + 1)\omega - a_r)^{\mathrm{T}} \tag{10}$$

结合式(6)，可得镇定控制律为

$$\boldsymbol{\tau} = (F, 0, T)^{\mathrm{T}} = \left(m_{11}u_1\sec(\beta), 0, \frac{(m_{22}m_{33} - m_{23}^2)u_2}{m_{22}}\right)^{\mathrm{T}} \tag{11}$$

3 稳定性分析

由 $$V_1 = \frac{1}{2}\boldsymbol{\chi}^{\mathrm{T}}\boldsymbol{\chi}$$

可得

$$\frac{\partial V_1}{\partial \boldsymbol{\chi}}\boldsymbol{B}(\boldsymbol{\chi})\boldsymbol{\alpha}_\zeta = -k_1[\rho\cos(\omega)]^2 - k_2\omega^2 \tag{12}$$

将式(9)、(12)代入式(8)可得

$$\dot{V}_2 = \frac{\partial V_1}{\partial \boldsymbol{\chi}}\boldsymbol{B}(\boldsymbol{\chi})\boldsymbol{\alpha}_\zeta - (\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta)^{\mathrm{T}}\boldsymbol{K}(\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta) = -k_1[\rho\cos(\omega)]^2 - k_2\omega^2 - (\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta)^{\mathrm{T}}\boldsymbol{K}(\boldsymbol{\zeta} - \boldsymbol{\alpha}_\zeta) \leqslant 0 \tag{13}$$

这表明系统式(7)的原点($\boldsymbol{\chi} = \mathbf{0}, \boldsymbol{\zeta} = \mathbf{0}$)是渐近稳定的，且

$$\lim_{t\to\infty}(\rho) = \lim_{t\to\infty}(\omega) = \lim_{t\to\infty}(v_c) = \lim_{t\to\infty}(r_\omega) = 0$$

式中：t 为仿真时间。

结合式(5)，可得

$$\lim_{t\to\infty}(\Phi)=\lim_{t\to\infty}(R)=0$$

由 $\lim_{t\to\infty}(\rho)=\lim_{t\to\infty}(v_c)=0$

可得 $$\lim_{t\to\infty}(X)=\lim_{t\to\infty}(Y)=\lim_{t\to\infty}(U)=\lim_{t\to\infty}(V)=0$$

由式(3)可知

$$\begin{cases}\lim_{t\to\infty}(X)=0\\ \lim_{t\to\infty}(Y)=0\\ \lim_{t\to\infty}(\Phi)=0\\ \lim_{t\to\infty}(U)=0\\ \lim_{t\to\infty}(V)=0\\ \lim_{t\to\infty}(R)=0\end{cases}\Leftrightarrow\begin{cases}\lim_{t\to\infty}(x)=0\\ \lim_{t\to\infty}(y)=0\\ \lim_{t\to\infty}(\psi)=0\\ \lim_{t\to\infty}(u)=0\\ \lim_{t\to\infty}(v)=0\\ \lim_{t\to\infty}(r)=0\end{cases}$$

推理可知系统式(1)、(2)的原点($\boldsymbol{\eta}=\mathbf{0},\boldsymbol{v}=\mathbf{0}$)是渐近稳定的，控制律式(11)能够使非对称欠驱动无人艇系统渐近稳定于原点。

4 仿真结果分析

采用上述设计控制律，选择某长度为 1.2 m、质量为 17.5 kg 的无人艇模型，进行无人艇镇定控制仿真试验[25]，模型参数见表 1，初始状态见表 2，控制参数见表 3。为说明本文提出的极坐标系下算法的优越性，选择传统笛卡尔直角坐标系下基于对称模型的反步法进行相同镇定控制仿真，所得位姿收敛结果见图 2～4，速度收敛结果见图 5～7，中间变量极径 ρ 和合速度 v_c 收敛响应曲线见图 8，中间角度变量 ω 和角速度变量 r_ω 收敛响应见图 9，无人艇镇定控制过程中的航行轨迹见图 10。在图 2～10 的仿真曲线中，S_1 组表示本文极坐标系下所设计控制器，S_2 组表示传统直角坐标系下所设计控制器；P_1 表示无人艇初始位置，P_2 表示镇定控制期望到达的目标原点。

表 1　无人艇模型参数

Tab. 1　Parameters of USV model

参数	数值	参数	数值
m_{11}	25.8	d_{11}	27.0
m_{22}	33.8	d_{22}	17.0
m_{33}	2.8	d_{33}	0.5
m_{23}	6.2	d_{23}	0.2
m_{32}	6.2	d_{32}	0.5

通过图 2～4 的位置和姿态收敛响应曲线可以看出本文提出的极坐标系下的分块反步控制方法(S_1 组)相比传统笛卡尔直角坐标系的反步控制方法(S_2 组)，收敛速度有 10 s 左右的提升；同时，S_2 组由于忽略了船舶模型对称性的影响，在位置收敛过程

表 2　无人艇初始状态

Tab. 2　Initial state of USV

位姿	数值	速度	数值
x/m	-3.5	$u/(\mathrm{m\cdot s^{-1}})$	5
y/m	1.0	$v/(\mathrm{m\cdot s^{-1}})$	1
ψ/rad	$-\pi/6$	$r/(\mathrm{rad\cdot s^{-1}})$	0.1

表 3　控制器参数

Tab. 3　Parameters of controller

参数	数值	参数	数值
k_1	0.2	k_2	1
k_3	0.8	k_4	1

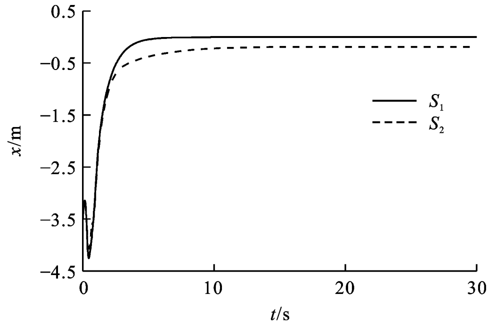

图 2　x 的收敛曲线

Fig. 2　Convergence curves of x

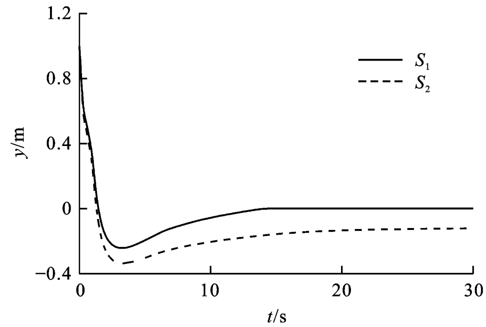

图 3　y 的收敛曲线

Fig. 3　Convergence curves of y

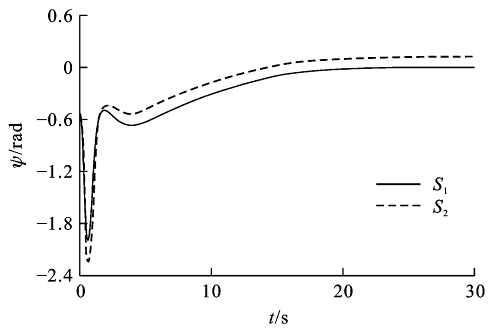

图 4　ψ 的收敛曲线

Fig. 4　Convergence curves of ψ

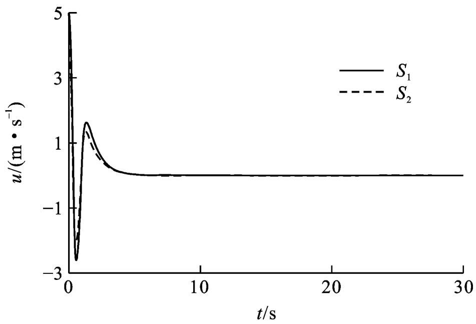

图 5　u 的收敛曲线

Fig. 5　Convergence curves of u

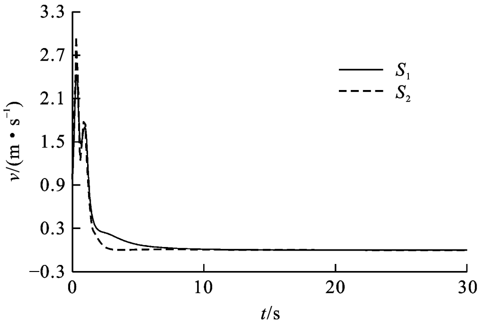

图 6　v 的收敛曲线

Fig. 6　Convergence curves of v

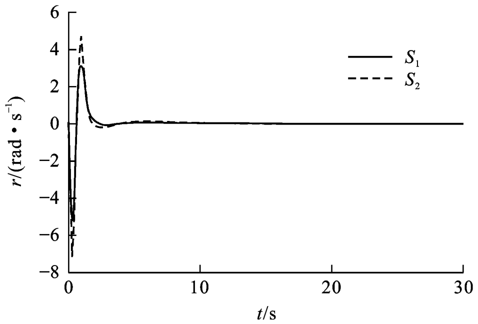

图 7　r 的收敛曲线

Fig. 7　Convergence curves of r

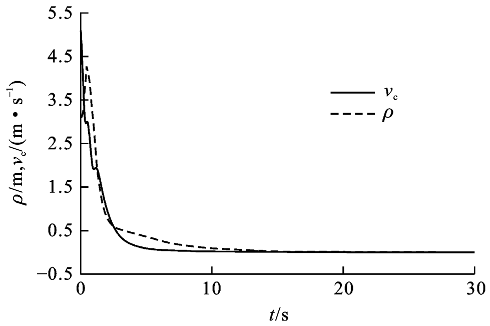

图 8　ρ 与 v_c 的收敛曲线

Fig. 8　Convergence curves of ρ and v_c

中出现了 0.3 m 左右的位置镇定误差，姿态收敛过程中出现了 10°(0.175 rad)左右的艏向角镇定误差，不符合无人艇控制系统中镇定控制精确性的要求。

从图 5～7 中可以看出 S_1 组控制方法相比 S_2 组，无人艇的速度信息收敛更加平缓，线速度超调量降低 0.6 m·s^{-1}左右，角速度超调量降低 2 rad·s^{-1}左右。

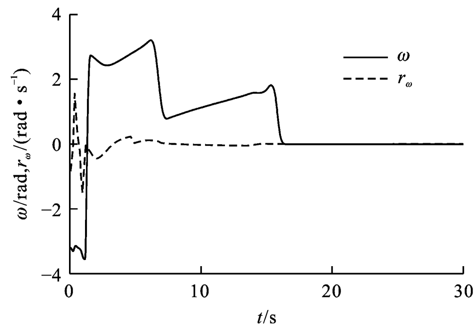

图 9　ω 与 r_ω 的收敛曲线

Fig. 9　Convergence curves of ω and r_ω

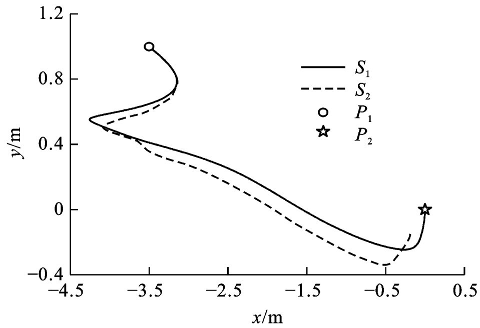

图 10　无人艇镇定过程中的航迹

Fig. 10　Stabilization trajectories of USV

从图 8、9 中可看出控制器设计过程中假设的中间变量在系统稳定同时能较快地收敛于 0，其中图 9 中 ω 出现了 3 次阶跃跳变，这是由于在镇定过程中极坐标系下的极角和漂角在位置(x, y)和速度(u,v)过零点时存在定义下的切换，不影响整体系统的最终收敛。

从图 10 中可看出在无人艇镇定控制过程中，本文所提出的基于非对称模型的极坐标系下分块反步控制方法，能够精确稳定地到达最终目标原点(P_2)，而常规基于对称模型的笛卡尔直角坐标系下反步控制方法存在 0.3 m 左右的镇定误差而无法满足无人艇系统精确控制的要求。

5　结　语

基于经典笛卡尔直角坐标系建立的无人艇运动学和动力学系统为典型的欠驱动系统，在引入极坐标系后，通过将极角、漂角和艏向角整合，可以将直角坐标系下的欠驱动问题简化为极坐标系下的全驱动问题。考虑无人艇前后不对称、系统惯性和阻尼系数矩阵非对角线元素存在非零项，借助微分同胚模型变换，将其简化为对称无人艇系统的标准形式。基于传统的 SISO 反步法，提出

了一种 MIMO 分块反步法,实现了非对称欠驱动无人艇系统的镇定控制。通过与传统基于对称模型的反步控制方法对比分析,在表 2 初始条件下,可知本文所提出方法收敛速度提升了约 10 s,位置镇定误差降低了约 0.3 m,艏向角镇定误差减小了约 10°,线速度超调量降低了约 0.6 m·s^{-1},角速度超调量降低了约 2 rad·s^{-1}。

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