Sliding Mode Control of a Remotely Operated Underwater Vehicle with Adaptive Fuzzy Dead-Zone Compensation

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Due to the great technological improvement obtained in the last decades, it became possible to use robotic vehicles for underwater exploration. During the execution of a certain task with a remotely operated underwater vehicle, the operator needs to monitor and control a number of parameters. If some of these parameters, as for instance position and attitude, could be controlled automatically, the teleoperation of the vehicle can be enormously facilitated. Based on experimental tests, it was verified that marine thrusters can exhibit dead-zone nonlinearities. This work describes the development of a variable structure control strategy for an underwater vehicle with a thrust system subject to dead-zone input.

1 Underwater Vehicle Dynamics

The equations of motion for underwater vehicles can be expressed, with respect to the body-fixed reference frame, in the following vectorial form [1]:

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{k}(\boldsymbol{\nu}) + \mathbf{h}(\boldsymbol{\nu}) + \mathbf{g}(\mathbf{x}) + \mathbf{d} = \boldsymbol{\tau} \tag{1}$$

where $\boldsymbol{\nu} = [\upsilon_x, \upsilon_y, \upsilon_z, \omega_x, \omega_y, \omega_z]$ is the vector of linear and angular velocities in the body-fixed reference frame, $\mathbf{x} = [x,\ y,\ z, \alpha, \beta, \gamma]$ represents the position and orientation with respect to the inertial reference frame, $\mathbf{M}$ is the inertia matrix, which accounts not only for the rigid-body inertia but also for the so-called hydrodynamic added inertia, $\mathbf{k}(\boldsymbol{\nu})$ is the vector of generalized Coriolis and centrifugal forces, $\mathbf{h}(\boldsymbol{\nu})$ represents the hydrodynamic quadratic damping, $\mathbf{g}(\mathbf{x})$ is the vector of generalized restoring forces (gravity and buoyancy), $\mathbf{d}$ stands for occasional disturbances, and $\boldsymbol{\tau}$ is the vector of control forces and moments.

It should be noted that in the case of remotely operated underwater vehicles (ROV), the metacentric height is sufficiently large to provide the self-stabilization of roll (α) and pitch (β) angles. This particular constructive aspect also allows the order of the dynamic model to be reduced to four degrees of freedom, $\mathbf{x} = [x,\ y,\ z, \gamma]$, and the vertical motion (heave) to be decoupled from the motion in the horizontal plane.

Regarding the thrust forces, the steady-state axial thrust T produced by marine thrusters is presented in the literature [2] as proportional to the square of propeller's angular velocity Ω. This quadratic relationship can be conveniently represented by $T = C_T\,\Omega|\Omega|$, where C_T is a function of the advance ratio and depends on constructive characteristics of each thruster. Nevertheless, according to experimental results (see Fig. 1), marine thrusters may also exhibit non-smooth nonlinearities such as dead-zones. Dead-zone is a hard nonlinearity, frequently encountered in many industrial actuators, and its presence can drastically reduce control system performance and lead to limit cycles in the closed-loop system. Figure 1 shows a comparative analysis between some experimental results and the conventional thrust model, as well as the proposed dead-zone model:

$$T = D(\Omega|\Omega|) = \begin{cases} m_l\,(\Omega|\Omega| - \delta_l) & \text{if} \quad \Omega|\Omega| \le \delta_l \\ 0 & \text{if} \quad \delta_l < \Omega|\Omega| < \delta_r \\ m_r\,(\Omega|\Omega| - \delta_r) & \text{if} \quad \Omega|\Omega| \ge \delta_r \end{cases} \tag{2}$$

The experiments were carried out in a wave channel with the thruster units of a small remotely operated underwater vehicle, developed at the Institute of Mechanics and Ocean Engineering of the Hamburg University of Technology. The ROV is equipped with eight thrusters for dynamic positioning and a passive arm for position and attitude measurement. A picture of the experimental underwater vehicle is presented in Fig. 2.

On this basis, in the next section, the control scheme presented in [1] is improved in order to deal with remotely operated underwater vehicles subject not only to model uncertainties and external disturbances, but also to dead-zones in the thrust system.

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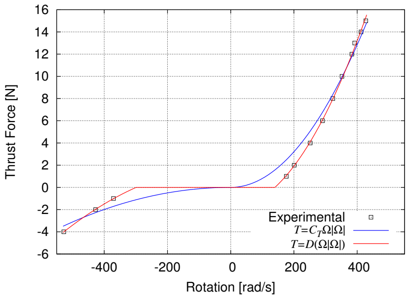

Fig. 1 Comparative analysis between experimental data and two thrust models.

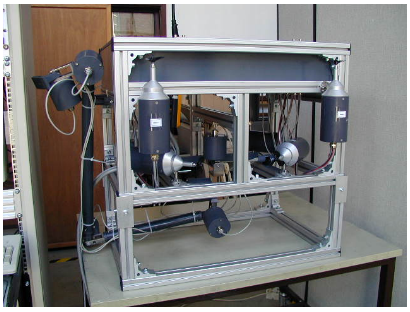

Fig. 2 The experimental remotely operated underwater vehicle.

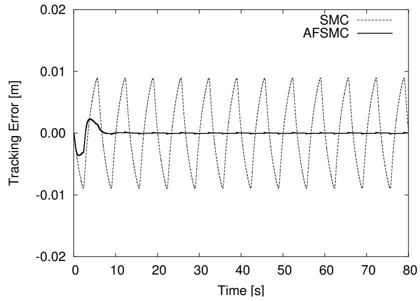

Fig. 3 Tracking error for the depth regulation with $z_d = 0.5[1 - \cos(0.1\pi t)]$.

2 Dynamic Positioning System

The control law for each degree of freedom can be easily designed with respect to the inertial reference frame. On this basis, considering that the restoring forces could be passively compensated and that $\dot{\mathbf{x}} = \mathbf{J}(\mathbf{x})\boldsymbol{\nu}$, $\boldsymbol{\nu} = \mathbf{J}^{-1}(\mathbf{x})\dot{\mathbf{x}}$ and $\dot{\boldsymbol{\nu}} = \dot{\mathbf{J}}^{-1}\dot{\mathbf{x}} + \mathbf{J}^{-1}\ddot{\mathbf{x}}$, where $\mathbf{J}(\mathbf{x})$ is the Jacobian transformation matrix, the equations of motion of an underwater vehicle, with respect to the inertial reference frame, becomes $\bar{\mathbf{M}}\ddot{\mathbf{x}} + \bar{\mathbf{k}} + \bar{\mathbf{h}} + \bar{\mathbf{d}} = \bar{\boldsymbol{\tau}}$, where $\bar{\mathbf{M}} = \mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\mathbf{J}^{-1}$, $\bar{\mathbf{k}} = \mathbf{J}^{-\mathrm{T}}\mathbf{k} + \mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\dot{\mathbf{J}}^{-1}\dot{\mathbf{x}}$, $\bar{\mathbf{h}} = \mathbf{J}^{-\mathrm{T}}\mathbf{h}$, $\bar{\mathbf{d}} = \mathbf{J}^{-\mathrm{T}}\mathbf{d}$ and $\bar{\boldsymbol{\tau}} = \mathbf{J}^{-\mathrm{T}}\boldsymbol{\tau}$. Finally, in order to develop the control law with a decentralized approach, the equations of motion can be rewritten as follows

$$\ddot{x}_i = \bar{m}_i^{-1}(\bar{\tau}_i - \bar{k}_i - \bar{h}_i - \bar{d}_i); \quad i = 1, 2, 3, 4, \tag{3}$$

where x_i, $\bar{\tau}_i$, $\bar{k}_i$, $\bar{h}_i$ and $\bar{d}_i$ are the components of $\mathbf{x} = [x, y, z, \gamma]$, $\bar{\boldsymbol{\tau}}$, $\bar{\mathbf{k}}$, $\bar{\mathbf{h}}$ and $\bar{\mathbf{d}}$, respectively. Concerning $\bar{m}_i$, it represents the main diagonal terms of $\mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\mathbf{J}^{-1}$. The off-diagonal terms of $\mathbf{J}^{-\mathrm{T}}\mathbf{M}\,\mathbf{J}^{-1}$ are incorporated in the vector $\bar{\mathbf{d}}$.

Considering the saturation function as the smooth approximation to the ideal relay, and $s_i = \dot{\tilde{x}}_i + \lambda_i \tilde{x}_i$, the control law for each degree of freedom could stated as follows

$$\bar{\tau}_i = \hat{\bar{k}}_i + \hat{\bar{h}}_i + \hat{\bar{d}}_i + \hat{\bar{m}}_i\left(\ddot{x}_{d_i} - \lambda_i \dot{\tilde{x}}_i\right) - K_i\,\mathrm{sat}(s_i/\phi_i) \tag{4}$$

where $\hat{\bar{m}}_i$, $\hat{\bar{k}}_i$ and $\hat{\bar{h}}_i$ stands for estimates of $\bar{m}_i$, $\bar{k}_i$ and $\bar{h}_i$, respectively. The gain of each controller should be carefully determined in order to ensure the global stability of the closed-loop system, and robustness with respect to disturbances and uncertainties, *i.e.*, $K_i \geq \mathcal{D}_i + \hat{\bar{m}}_i \mathcal{G}_i \eta_i + |\hat{\bar{d}}_i| + \hat{\bar{m}}_i(\mathcal{G}_i - 1)|\ddot{x}_{d_i} - \lambda_i \dot{\tilde{x}}_i|$, where η_i are strictly positive constants related to the reaching time of each controller and $\mathcal{G}_i = \sqrt{\bar{m}_{\max}/\bar{m}_{\min}}$. Regarding $\mathcal{D}_i$, this term should be defined for each controller in order to compensate the uncertainties of the respective components of vectors $\bar{\mathbf{k}}$ and $\bar{\mathbf{h}}$, and perturbations provided by $\bar{\mathbf{d}}$, $\left|\Delta\bar{k}_i + \Delta\bar{h}_i + \bar{d}_i\right| \leq \mathcal{D}_i$. The saturation function, $\mathrm{sat}(\cdot)$, is adopted in order to eliminate chattering, but it leads to the formation of a thin boundary layer neighboring each switching surface and to an inferior tracking performance.

In order to enhance the tracking performance, in this work, an adaptive fuzzy inference system is embedded inside the boundary layer, to cope with the uncertainties and disturbances that can arise, as well as the dead-zone input. The adopted fuzzy inference system was the zero order TSK (Takagi–Sugeno–Kang). Considering $\hat{\bar{\tau}}_i = \hat{\bar{k}}_i + \hat{\bar{h}}_i + \hat{\bar{d}}_i + \hat{\bar{m}}_i\left(\ddot{x}_{d_i} - \lambda_i \dot{\tilde{x}}_i\right)$, the final output of the fuzzy inference is $\hat{\bar{d}}_i(\hat{\bar{\tau}}_i) = \hat{\mathbf{D}}_i^{\mathrm{T}}\boldsymbol{\Psi}_i(\hat{\bar{\tau}}_i)$, where $\hat{\mathbf{D}}_i = [\hat{D}_{i_1}, \hat{D}_{i_2}, \ldots, \hat{D}_{i_N}]$ is the vector containing the attributed values $\hat{D}_{i_r}$ to each rule r, $\boldsymbol{\Psi}_i(\hat{\bar{\tau}}_i) = [\psi_{i_1}, \psi_{i_2}, \ldots, \psi_{i_N}]$ is a vector with components $\psi_{i_r} = w_{i_r}/\sum_{r=1}^{N} w_{i_r}$ and w_{i_r} is the firing strength of each rule. In order to obtain the most suitable values for $\hat{\bar{d}}_i(\hat{\bar{\tau}}_i)$, the vectors of adjustable parameters will be automatically updated according to $\dot{\hat{\mathbf{D}}}_i = -\varphi_i\, s_i\, \boldsymbol{\Psi}_i(\hat{\bar{\tau}}_i)$, where φ_i are strictly positive constants related to the adaptation rate. Figure 3 gives the tracking error related to the depth regulation of the ROV.

3 Concluding Remarks

In this paper, the dynamic positioning system of remotely operated underwater vehicles subject to dead-zones in the thrust system is considered. As observed in Fig. 3, the proposed adaptive fuzzy sliding mode controller (AFSMC) provides a smaller tracking error when compared with the conventional sliding mode controller (SMC).

References

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