PRELIMINARY SIMULATION STUDIES OF A NEW FOUR-QUADRANT PROPELLER THRUST CONTROLLER APPLIED TO UNDERWATER VEHICLES

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Abstract: In this paper a recently reported four-quadrant nonlinear thrust controller for marine propellers is applied to the velocity control of an underwater vehicle. The controller, designed for fixed pitch electrically driven propellers, is based on a shaft speed control and employs an estimate of the propeller torque loss. A simulation study is performed in order to compare the presented approach with the conventional shaft speed and torque propeller controllers.

Keywords: Underwater vehicle, marine propulsion, thrust control, state estimation, nonlinear vehicle control.

1. INTRODUCTION

The use of underwater vehicles is becoming more widespread. The precision and complexity of the required tasks need an increase of the maneuvering accuracy and the propulsion system plays a key role in the achievement of the missions. Thruster modeling and control has been subject to a growing interest in the last years (Yoerger *et al.* 1990), (Healey *et al.* 1995), (Whitcomb and Yoerger 1995), (Fossen and Blanke 2000), (Bachmayer *et al.* 2000), (Smogeli 2006) and (Pivano *et al.* 2007). The primary objective of low level thruster control is to obtain the desired thrust from the propeller regardless the environmental state. The knowledge of the value of the propeller thrust and torque is thus fundamental to achieve high control performances. In practice, propeller systems are not usually equipped with thrust and torque sensors therefore thrust losses are not directly measured.

As reported in (Smogeli *et al.* 2005), today's industrial standard for fixed pitch propeller is shaft speed control in which the desired shaft speed is computed from the desired thrust through a static mapping. Also torque and power control and combination of those have been developed and implemented (see for example Blanke and Nielsen (1990), Smogeli *et al.* (2005) and Indiveri *et al.* (2006)). These controllers do not use any information about the

propeller working condition. In consequence, thrust control may be poor when thrust losses occur.

In this paper a recently reported four-quadrant nonlinear thrust controller (Pivano *et al.* 2007) is applied to underwater vehicles. The controller is designed for fixed pitch electrically driven propellers and controls the shaft speed. The shaft speed reference is computed from the thrust reference and from an estimate of the propeller torque loss, which is estimated with a nonlinear observer. In this way the controller is able to compensate for the thrust loss. The mapping to compute the desired shaft speed in Pivano *et al.* (2007) is improved. This is done in order to reduce the high control activity experienced in Pivano *et al.* (2007) for values of the shaft speed and the vessel speed in the 2nd and 4th quadrants. A simulation study is performed in order to evaluate the performance of the vehicle when employing the proposed method compared to the conventional shaft speed and torque propeller controllers.

2. VEHICLE SPEED CONTROLLER

Without loss of generality, we consider an underwater vehicle moving in surge equipped with one single propeller aft of the hull. If, as in Fossen (2002) and Smallwood and Whitcomb (2004), we neglect ocean

currents, then the 1-dimensional vehicle surge dynamics is given by

$$m_u \dot{u} + d_l u + d_q u |u| = (1-t) T_p, \quad (1)$$

where u is the vehicle speed, $m_u > 0$ is the vehicle mass including the hydrodynamic added mass, $d_l > 0$ and $d_q > 0$ are the linear and quadratic hydrodynamic damping coefficients and $0 < t < 1$ is the thrust deduction number introduced to account for the drag created by the propeller (Lewis 1988). The thrust produced by the propeller is defined T_p . We design a control law for the vehicle to track a desired speed reference u_d where $u_d, \dot{u}_d$ are continuous and bounded. At this point we assume that the propeller produces the desired thrust $T_p = T_{p_d}(u_d, \dot{u}_d, u)$ instantaneously and later we will consider the effect of the propeller dynamics. We employ the following control law that includes a feed-forward part, a proportional action and an integral action to ensure convergence in presence of constant disturbances:

$$T_{p_d} = \frac{1}{(1-t)} [m_u \dot{u}_d + d_l u_d - (k_I + \gamma k_P) e_1 - k_P e_2 + d_q (-\gamma e_1 + u_d) |-\gamma e_1 + u_d|], \quad (2)$$

where $e_1 = \int_0^t (u(\tau) - u_d(\tau)) d\tau$ and $e_2 = u - u_d$ are the control error variables for position and velocity, respectively.

Using (2), the error dynamics can be written as

$$\begin{aligned} \dot{e}_1 &= e_2 \\ \dot{e}_2 &= -\frac{d_l}{m_u} e_2 - \frac{d_q}{m_u} (e_2 + u_d) |e_2 + u_d| - \frac{k_P}{m_u} e_2 \\ &\quad - \frac{(k_I + \gamma k_P)}{m_u} e_1 + \frac{d_q}{m_u} (-\gamma e_1 + u_d) |-\gamma e_1 + u_d|. \end{aligned} \quad (3)$$

Proposition 1. If the gains γ, k_I and k_P are chosen such that

A1 $\gamma > 0$,

A2 $k_P > 0, k_P > m_u \gamma - d_l$,

A3 $k_I > 0, k_I > -m_u \gamma^2 + d_l \gamma$,

then the control error dynamics (3) is uniformly globally exponentially stable (UGES).

PROOF. Let the Lyapunov function candidate be $V_1 = \frac{1}{2} e^T P e$, where $e = [e_1 \ e_2]^T$ and P is positive definite such that

$$P = \begin{bmatrix} p_{11} + p_{22} \gamma^2 & \gamma p_{22} \\ \gamma p_{22} & p_{22} \end{bmatrix}. \quad (4)$$

This implies $p_{11} > 0$ and $p_{22} > 0$. Taking the time derivative of V_1 along the trajectory of the system (3) we obtain

$$\begin{aligned} \dot{V}_1 &= -\frac{p_{22}}{m_u} \gamma (k_I + \gamma k_P) e_1^2 \\ &\quad + \left(p_{11} - p_{22} \left(-\gamma^2 + \frac{\gamma d_l}{m_u} + \frac{2\gamma k_P}{m_u} + \frac{k_I}{m_u} \right) \right) e_1 e_2 \\ &\quad - p_{22} \left(-\gamma + \frac{d_l}{m_u} + \frac{k_P}{m_u} \right) e_2^2 \\ &\quad - \frac{p_{22} d_q}{m_u} \Gamma(e_1, e_2, u_d) (\gamma e_1 + e_2), \end{aligned} \quad (5)$$

where

$$\Gamma(e_1, e_2, u_d) = (e_2 + u_d) |e_2 + u_d| - (-\gamma e_1 + u_d) |-\gamma e_1 + u_d|. \quad (6)$$

The last term in (5) is always non positive since

$$\Gamma(e_1, e_2, u_d) (\gamma e_1 + e_2) = [g(a) - g(b)](a - b), \quad (7)$$

where $a = e_2 + u_d$, $b = -\gamma e_1 + u_d$ and $g(r) = r |r|$ is a non decreasing function. Choosing

$$p_{11} = p_{22} \left(-\gamma^2 + \frac{\gamma d_l}{m_u} + 2 \frac{\gamma k_P}{m_u} + \frac{k_I}{m_u} \right), \quad (8)$$

we cancel the cross term in (5). This is possible because, due to the assumptions A2 and A3, the term inside the parenthesis is positive. Using (7) and (8), (5) becomes

$$\dot{V}_1 \leq -e^T Q e, \quad (9)$$

where

$$Q_1 = \begin{bmatrix} \frac{p_{22}}{m_u} \gamma (k_I + \gamma k_P) & 0 \\ 0 & p_{22} \left(-\gamma + \frac{d_l}{m_u} + \frac{k_P}{m_u} \right) \end{bmatrix} \quad (10)$$

is positive definite due to assumptions A1 and A2. ■

3. PROPELLER THRUST CONTROLLER

The shaft speed reference is derived as follows: first the desired propeller torque Q_{p_d} is computed from the desired thrust T_{p_d} using the standard propeller characteristics; second the desired shaft speed is computed from Q_{p_d} and an estimate of the torque loss $\hat{\Delta}_q$, obtained with a nonlinear observer.

3.1 Propeller modeling

We consider a fixed pitch propeller attached to a shaft driven by an electric servo motor. This is the most common solution adopted for underwater vehicles. The shaft rotates at the angular speed ω . Its dynamics can be written as

$$J_m \dot{\omega} = Q_m - Q_p - Q_f(\omega), \quad (11)$$

where J_m is moment of inertia of the shaft including the propeller, $Q_f(\omega)$ is the shaft friction torque which depends on the shaft speed, Q_m is the motor torque, controlled by the motor drive based on the reference Q_{m_d} . Q_p and T_p are the propeller load torque and the propeller thrust, respectively. The friction torque includes both Coulomb and linear viscous effect. We adopt the following approximate model for the friction

$$Q_f(\omega) = k_{f_1} \frac{2}{\pi} \arctan\left(\frac{\omega}{\epsilon}\right) + k_{f_2} \omega, \quad (12)$$

where the coefficients k_{f_i} and ϵ are constant and positive. In order to avoid the singularity in zero, the Coulomb effect, usually written as a $\text{sign}(\omega)$, has been replaced by the function $\frac{2}{\pi} \arctan(\frac{\omega}{\epsilon})$ with a small positive ϵ (Bachmayer *et al.* 2000) (Pivano *et al.* 2006a). Fig. 1 shows a sketch of the system.

Fig. 1. Sketch of the propeller system.

Modeling the thrust and torque produced by a propeller is a complicated task, since it is difficult to develop a finite-dimensional analytical model from

the laws of physics. This is mainly due to the difficulty to model the flow dynamics, especially when the flow is not uniform (see Bachmayer *et al.* (2000), Pivano *et al.* (2006b) and references therein). Besides that, the thrust and torque depend also on the propeller geometrical parameters (i.e. propeller diameter, pitch angle, etc.), the non-dimensional parameters advance number J and Reynolds number, the propeller submergence and environmental state (waves, currents, etc.). In order to be able to estimate the propeller torque loss, Q_p is represented by the torque produced at zero advance speed, that is the propeller is deeply submerged and not subjected to losses, plus a term Δ_q that incorporates the torque losses (Pivano *et al.* 2007):

$$Q_p = G_{Q_{p,n}} |\omega| \omega + \Delta_q, \quad (13)$$

where

$$G_{Q_{p,n}} = \begin{cases} G_{Q_p}, & \omega \geq 0 \\ G_{Q_n}, & \omega < 0. \end{cases} \quad (14)$$

The terms G_{Q_p} and G_{Q_n} are positive constants and of different magnitudes since the propeller usually is not symmetric. When the motor is driven by a current amplifier for example, precise torque control is possible and the dynamics of the electrical part of the system (frequency converter, stator and rotor), usually faster than the shaft dynamics, can be neglected. The control input can thus be represented by $Q_m = Q_{m,d}$. Both Q_m and ω are assumed measurable. The term Δ_q is represented by a Markov-like process with time constant τ driven by a bounded noise signal w . This model, motivated by experiments presented in Pivano *et al.* (2007), is written as

$$\dot{\Delta}_q = -\frac{1}{\tau} \Delta_q + w. \quad (15)$$

The noise w represents the contribution of all the phenomena that can generate torque losses. Grouping the nonlinearities in the function $\psi(\omega)$, the system can be rewritten as:

$$J_m \dot{\omega} = Q_m - \psi(\omega) - k_{f_2} \omega - \Delta_q, \quad (16)$$

where Δ_q is given by (15) and

$$\psi(\omega) = G_{Q_{p,n}} |\omega| \omega + \frac{2k_{f_1}}{\pi} \arctan\left(\frac{\omega}{\epsilon}\right).$$

3.2 Torque loss observer

A nonlinear observer with gain l_1 and l_2 is employed to estimate the torque loss $\hat{\Delta}_q$ and the shaft speed $\hat{\omega} = \hat{y}$:

$$J_m \dot{\hat{\omega}} = Q_m - \psi(\hat{\omega}) - k_{f_2} \hat{\omega} - \hat{\Delta}_q + l_1 (y - \hat{y}) \quad (17)$$

$$\dot{\hat{\Delta}}_q = -\frac{1}{\tau} \hat{\Delta}_q + l_2 (y - \hat{y}) \quad (18)$$

$$y = \omega. \quad (19)$$

As proved in Pivano *et al.* (2007), if there exist two positive constants a_{11} and a_{22} , and the gains are chosen such that

$$\mathbf{B1} \quad l_1 > -k_{f_2},$$

$$\mathbf{B2} \quad \left| \frac{a_{11}}{J_m} + a_{22} l_2 \right| < 2 \sqrt{a_{11} a_{22} \left(\frac{k_{f_2} + l_1}{\tau J_m} \right)},$$

the estimates converge to a ball around the actual values. This is due to the observer error dynamics being input-to-state stable (ISS) with respect to w . An estimate of the propeller torque can be computed from

$$\hat{Q}_p = G_{Q_{p,n}} |\hat{\omega}| \hat{\omega} + \hat{\Delta}_q. \quad (20)$$

3.3 Shaft speed reference generator

The first step in order to compute the shaft speed reference is to determine the propeller torque reference $Q_{p,d}$. This can be obtained from the standard propeller characteristics employing an estimate of the advance number J :

$$J = \frac{2\pi u_a}{\omega D}, \quad (21)$$

where D is the propeller disc diameter and u_a is the advance speed, i.e. the speed of the inlet water to the propeller disc. The thrust and torque standard propeller coefficients K_T and K_Q are computed as:

$$K_T = \frac{4\pi^2 T_p}{\rho |\omega| \omega D^4}, \quad (22)$$

$$K_Q = \frac{4\pi^2 Q_p}{\rho |\omega| \omega D^5}. \quad (23)$$

Using the relations (22) and (23) in combination with the thrust reference, the desired propeller torque $Q_{p,d}$ is computed as:

$$Q_{p,d} = \frac{1}{\hat{G}_{QT}(\hat{J})} T_{p,d}, \quad (24)$$

where $\hat{G}_{QT}(\hat{J})$ is an estimate of

$$G_{QT}(J) = \frac{T_p}{Q_p} = \frac{K_T |J|}{DK_Q |J|}, \quad (25)$$

such that

$$\hat{G}_{QT}(\hat{J}) = \frac{K_T |\hat{J}|}{DK_Q |\hat{J}|}. \quad (26)$$

Remark 2. The thrust torque ratio $G_{QT}(J)$ is based on the propeller characteristic measured in steady-state conditions. In Pivano *et al.* (2006a) it has been experimentally demonstrated that the relationship between thrust and torque is stable and the ratio $G_{QT}(J)$ is a good approximation of the thrust torque ratio also for transient conditions. This allows us to use the propeller characteristics to compute the desired torque from the desired thrust.

To compute $G_{QT}(\hat{J})$, an estimate $\hat{J}$ of the advance number is derived employing the estimated propeller torque. Using $\hat{Q}_p$ instead of Q_p in (23) we compute the estimate $\hat{K}_Q$. Combining the value of $\hat{K}_Q$ with the K_Q curve we can derive the value of $\hat{J}$. Fig. 2 (a) shows the measured K_Q curve of the propeller used in the experiments presented in Pivano *et al.* (2006a). As shown in Fig. 2 (a), the K_Q curve is not invertible in the all plotted range. The problem of not being able to invert the K_Q curve is solved by approximating the value of $G_{QT}(J)$ by $G_{QT}(0)$ in zone 1. When the propeller works at negative values of J , the advance speed u_a and the shaft speed ω have opposite signs. The

propeller tries to reverse the inlet flow causing turbulences. This can result in quick variations of the propeller load (Pivano *et al.* 2006a) and consequently oscillations of the value K_Q and $\hat{K}_Q$. In this situation, even a constant value of the desired thrust could result in fast variation on Q_{pd} . This can cause high control activity, as experienced in Pivano *et al.* (2007), increasing the wear-and-tear of the system. This is avoided by approximating $G_{QT}(J)$ by a constant in zone 1. The advance number J is limited to the range $[-1.5, 1.1]$ for positive ω and $[-1.5, 1.0]$ for negative ω . This is the usual working range for the propeller from which the characteristics are obtained. Fig. 2 (b) shows the ratio between the propeller thrust and torque $G_{QT}(J)$ computed with (25) and its approximation $G_{QT}(\hat{J})$. The plot reefers to positive shaft speed ω ; the plot for negative speed is analogous

Fig. 2. K_Q characteristic for $\omega \geq 0$ and the ratio between thrust and torque for $\omega \geq 0$.

Given the desired propeller torque Q_{pd} , the desired shaft speed $\bar{\omega}_d$ is computed by inverting (13) and using the estimated torque loss $\hat{\Delta}_q$:

$$\bar{\omega}_d = \sqrt{\frac{Q_{pd} - \hat{\Delta}_q}{G_{Q_{p,n}}}} \text{sign}(Q_{pd} - \hat{\Delta}_q). \quad (27)$$

To generate a smooth reference signal ω_d and $\dot{\omega}_d$, we employ a second order low pass filter with cutoff frequency equal to ω_c and relative damping factor ξ :

$$\ddot{\omega}_d + 2\omega_c\xi\dot{\omega}_d + \omega_c^2\omega_d = \omega_c^2\bar{\omega}_d. \quad (28)$$

The filter is also needed because the time derivative of $\bar{\omega}_d$, used in the feed-forward term of the controller, is infinity when $Q_{pd} - \hat{\Delta}_q = 0$.

3.4 Control law

We employ the following control law that includes a feed-forward part, a proportional action and an integral action to ensure convergence in presence of constant disturbances:

$$Q_m = J_m\dot{\omega}_d + \hat{\Delta}_q + \psi(-\alpha e_3 + \omega_d) + k_{f_2}\omega_d - (n_I + \alpha n_P)e_3 - n_P e_4, \quad (29)$$

where the control errors are defined by $e_3 = \int_0^t (\omega(\tau) - \omega_d(\tau))d\tau$ and $e_4 = \omega - \omega_d$. If the gains α , n_I and n_P are chosen such that

C1 $\alpha > 0$,

C2 $n_P > 0$, $n_P > \alpha J_m - k_{f_2}$,

C3 $n_I > 0$, $n_I > -J_m^2\alpha + \alpha k_{f_2}$,

then the origin of the overall error dynamics (observer + controller) is ISS with respect to w . See Pivano *et al.* (2007) for a proof.

4. SIMULATION RESULTS

The simulation is performed with the parameters given in Tab. 1. The propeller considered, employed in the experiments presented in Pivano *et al.* (2006a) and Pivano *et al.* (2007), is a fixed pitch type with four blades and pitch ratio equal to 1. The shaft dynamics (11) is simulated with the friction torque model given in (12). The propeller thrust and torque are computed with the four-quadrant propeller characteristics C_T and C_Q (Pivano *et al.* 2006a):

$$T_p = \frac{1}{2}C_T\rho V_r^2 A_0, \quad (30)$$

$$Q_p = \frac{1}{2}C_Q\rho V_r^2 A_0 D, \quad (31)$$

where A_0 is the propeller disc area and V_r is the relative advance velocity:

$$V_r^2 = u_a^2 + (0.7R\omega)^2. \quad (32)$$

The advance speed u_a is computed from the vehicle speed and the wake fraction number w_f as $u_a = u(1 - w_f)$ (Lewis 1988). For negative vehicle speed we assume that the vehicle body does not disturb the inlet water to the propeller therefore w_f is considered equal to zero. White noise is added to the shaft speed measurement signal.

The vehicle dynamics (1) is simulated employing the thrust produced by the propeller where the propeller thrust reference is computed with (2). The vehicle speed is assumed to be measured with a Doppler velocity log (DVL) measurement with 10Hz of updating frequency. The speed measurement error is added by considering a 1200Hz DVL unit (DVL WHN 1200 Workhorse Navigator from Teledyne Rd Instruments) with a total error standard deviation equal to $\pm 0.5\% + 0.01$ m/s.

The proposed controller, defined as the thrust controller, is compared with the conventional shaft speed and torque controllers. Experimental validation of shaft speed and torque control has been presented in Smogeli *et al.* (2005) and in Pivano *et al.* (2007). Both the conventional controllers use the nominal values of the propeller characteristics for $J = 0$. For the shaft speed controller, the demanded shaft speed $\bar{\omega}_d$ is calculated as

$$\bar{\omega}_d = \sqrt{\frac{4\pi^2 |T_{pd}|}{\rho D^4 K_T|_{J=0}}} \text{sign}(T_{pd}). \quad (33)$$

To control the shaft speed, the control law (29) and the reference filter in (28) are employed. For a torque controller with friction compensation, the demanded motor torque is computed as

$$Q_{m_d} = \frac{1}{G_{QT}(0)} T_{p_d} + Q_f(\omega). \quad (34)$$

Figures 3, 4 and 5 present the simulation result obtained employing the three propeller controllers. The desired vehicle speed is a sinusoidal signal of 2 m/s amplitude and the vehicle initial speed is set equal to 1 m/s. The thrust reference plotted in all figures, does not correspond to the actual T_{p_d} but it is obtained from (2) in the ideal case where the propeller is able to produce the required thrust instantaneously. It is possible to see that the thrust produced using the proposed controller is closer to the ideal case compared to the traditional controllers. Consequently the vehicle speed follows more accurately the reference. The traditional shaft speed controller provides the worst result with regard to the thrust production, resulting in a large vehicle speed error. The torque controller performs more accurately than the classical shaft speed controller. The thrust error is mainly due to the use of a constant mapping between thrust and torque while, as shown in Fig. (2), this varies for different values of J . Also in the classical torque controller there is not a compensation term for the shaft moment of inertia. The thrust controller performs better than the torque controller because it account for variation in the thrust torque ratio and also it compensates for the shaft moment of inertia. The same conclusion was experimentally found in Smogeli *et al.* (2005) and in Pivano *et al.* (2007).

Remark 3. The vehicle performance is also influenced by the choice of controller gains in (2). If the vehicle speed measurement is not very noisy, employing high gains will lead to an improvement of the performance for all the propeller controllers.

Remark 4. A vehicle with larger hydrodynamic damping coefficients than the ones simulated, will require larger thrust at the same vehicle speed, resulting in greater shaft speeds. The propeller will work at lower values of J and hence near to the nominal condition $J = 0$, where the three propeller controllers perform equally well.

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
m_u [Kg]	200	ϵ	$1 \cdot 10^{-3}$
d_l [Kg/s]	50	τ [s]	10
d_q [Kg/m]	30	l_1	3
t	0.1	l_2	-80
k_I	5	τ [s]	10
k_P	2	n_P	0.5
γ	0.1	n_I	0.1
J_m [kg·m ²]	0.09	α	0.1
k_{f1} [$\frac{s \cdot N}{m \cdot rad}$]	0.3	ω_c [rad/s]	44
k_{f2} [$\frac{s \cdot N}{m \cdot rad}$]	0.09	ξ	1

5. CONCLUSION

In this paper a four-quadrant nonlinear thrust controller was applied to an underwater vehicle. The proposed scheme was compared to shaft speed and torque controllers showing better performances in terms of the produced thrust. The accuracy of the thrust controller resulted in better vehicle performance.

Fig. 3. Propeller thrust controller: desired and actual vehicle speed (a), vehicle speed error (b), desired and actual thrust (c), thrust error (d), desired and actual shaft speed (e) and commanded motor torque (f).

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Fig. 4. Shaft speed controller: desired and actual vehicle speed (a), vehicle speed error (b), desired and actual thrust (c), thrust error (d), desired and actual shaft speed (e) and commanded motor torque (f).

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Fig. 5. Torque controller: desired and actual vehicle speed (a), vehicle speed error (b), desired and actual thrust (c), thrust error (d), shaft speed (e) and commanded motor torque (f).

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