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Switched Adaptive Scheme for Heading Control in Ships ⋆

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Abstract: This paper presents an adaptation scheme for the control of the heading in a ship. The proposed scheme consists on a series of linear controllers optimized for different values of the forward speed of the ship. As the ships accelerates from one speed level to the next, a different controller is selected to replace the previous one. Each individual controller consists of a two-degree of freedom optimal digital controller, with a feedback loop for disturbance rejection and a feedforward part for trajectory tracking. All are synthesized based on linear models using the theory of the Parametric Transfer Function. The adaptation scheme is then tested on a linear parameter-varying model, dependent on the ship's speed, to observe its qualitative behavior.

Keywords: Gain Scheduling; Heading Tracking; Parametric Transfer Function; Sampled-Data Systems.

1. INTRODUCTION

The dynamic response of a ship depends heavily on two descriptors: its loading state and its speed over the water. The first one, consisting on the load on board and its distribution to the ship, affects cargo vessels, like container ships, enormously. Military vessels, like frigates or destroyers, normally operate with a relatively invariant displacement and are therefore mainly affected by speed variations. Any controller to be deployed on a ship under these variable conditions would require some kind of adaptation for it to perform its task correctly.

This work presents such an adaptation scheme for a ship heading controller based on a switched scheme. Using the Parametric Transfer Function (PTF) approach, five 2-DoF controllers are designed for optimal disturbance rejection and trajectory tracking. Each controller is synthesized considering a linear dynamic model of the ship for a given forward speed. The five controllers are then tested on a linear varying parameters model, in which the characteristics of the ships are changed as the forward speed varies. As the speed changes from one region to the next, the controller corresponding to the new level kicks-in with a smooth action, maintaining optional heading tracking while keeping the variations on the rudder deflection small.

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Generic discussions about the theoretical basis of the work are presented in Section 2. The ship modeling and the synthesis of the controller are shown in sections 3 and 4, respectively. Simulation results showing the behavior of the controller appear in Section 5 while Section 6 presents some concluding remarks and directions for future work.

2. THE PARAMETRIC TRANSFER FUNCTION

Traditional methods for the design of digital controllers for continuous plants, so-called sampled-data systems, consist follow one of two possible approaches:

- Find a discrete model of the continuous plant and design a digital control law to be implemented.
- Synthesize an analog controller and obtain a discrete model of this controller for the digital implementation.

Either of those approaches misses the fact that the output of digital controllers is in fact a continuous signal which remains active between sampling instants.

In order to circumvent these issues, the concept of *Parametric Transfer Function* (PTF) was introduced by Rosenwasser and Lampe (2000). The PTF is a mathematical tool which can be used to represent both continuous and discrete systems simultaneously, making it specially suited for the analysis of sampled-data systems.

A system with input $x(t)$ and output $y(t)$ can be represented by an operator such that

$$y(t) = \mathsf{U}\left[x(t)\right]. \tag{1}$$

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Assuming that the input has the form $x(t) = e^{st}$, with s being a complex constant, the PTF $W(s,t)$ of the system is defined as

$$\mathsf{U}\left[e^{st}\right] = W(s,t)e^{st}. \tag{2}$$

Notice that the PTF depends on two parameters: $t \in \mathbb{R}$ and $s \in \mathbb{C}$. It is important to take into account that s is a general complex parameter with properties similar to those of the Laplace variable. It is, however, not identical to it, and confusion should be avoided.

Just like the traditional transfer functions for continuous and discrete systems are based on the Laplace and Z-transformations of the corresponding input and output signals, the PTF can be obtained by defining the *Discrete Laplace Transformation* (DLT). For a continuous signal $f(t)$ with Laplace image $F(s)$, the DLT is defined as

$$\mathcal{D}_f(T,s,t) = \sum_{k=-\infty}^{k=\infty} f(t+kT)e^{-ksT} \tag{3a}$$

$$\mathcal{D}_F(T,s,t) = \sum_{k=-\infty}^{k=\infty} F(s+kj\omega)e^{(s+kj\omega)t}, \tag{3b}$$

where $T > 0$ is a real parameter and $\omega = 2\pi/T$. For a discrete sequence $\{x_k\}$ the discrete Laplace transform takes the form

$$X^*(s) = \sum_{k=-\infty}^{k=\infty} x_k e^{-skT}. \tag{4}$$

The PTF can be then considered as an input-output representation of a system corresponding to the ratio of the DLT of the output to the DLT of the input. Since the DLT is defined both for continuous and discrete signals, it is possible to define the PTF for system with mixed inputs and outputs, like analog-to-digital or digital-to-analog converters.

The convergence criteria of the series in (3) to (4) plus some other properties and closed formulas for the computations of the series and PTFs for system commonly seen in practice are presented in detail within the work of Rosenwasser and Lampe (2000). These definitions and properties are used to formulate a single transfer function for a closed-loop system that includes discrete and continuous blocks simultaneously. Several different optimization problems can be then formulated on this basis.

3. THE PLANT

3.1 Linear Model

In this work we consider a simplified model of a container ship, following Ladisch (2004). A constant forward speed is assumed and the model is decoupled such that only the movements on the water plane are considered. The true heading angle, $\psi(t)$, is defined as the angle between the true North and the bow line of the ship. To steer the ship to a desired true heading angle the rudder aft of the ship is used, so the input variable is the rudder angle $\delta(t)$. If the variations of these variables are small with respect to an operating point such that a linear approximation can be used, the dynamics of the ship can then be described, using the so-called Nomoto model (Nomoto et al., 1957),

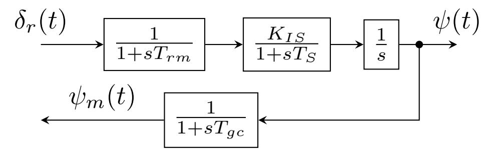

Fig. 1. Block diagram of the ship's heading model, from the rudder command $\delta_r(s)$, to the actual $\psi(s)$ and the measured $\psi_m(s)$ headings.

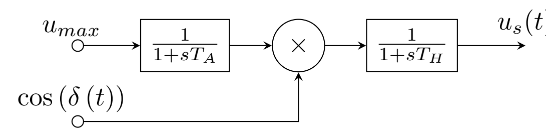

Fig. 2. Block diagram of the ship's forward speed model.

by a PT_1 transfer function from the rudder angle $\delta(t)$ to the rate of change of the heading angle $r(t) = \dot{\psi}(t)$

$$F(s) = \frac{r(s)}{\delta(s)} = \frac{K_{IS}}{1+sT_S}, \tag{5}$$

which is then integrated to obtain the actual heading angle $\psi(t)$ from the rudder position $\delta(t)$. Since the rudder machine in the ship has some inertia, a first order transfer function $H(s)$ between the commanded rudder angle $\delta_r(t)$ and its actual value $\delta(t)$ is normally used to take this inertia into account. Considering this, the full transfer function from the commanded rudder angle $\delta_r(t)$ to the heading angle $\psi(t)$ is

$$\frac{\psi(s)}{\delta_r(s)} = \frac{1}{s}F(s)H(s) = \frac{1}{s}\cdot\frac{K_{IS}}{1+sT_S}\cdot\frac{1}{1+sT_{rm}}. \tag{6}$$

In order to close a control loop, the dynamics of the compass used to obtain the measured heading $\psi_m(t)$ (also known as compass heading) from the true heading $\psi(t)$ are included to complement the model. This element is also modeled by a simple PT_1 transfer function of the form

$$G(s) = \frac{\psi_m(s)}{\psi(s)} = \frac{1}{1+sT_{gc}}. \tag{7}$$

The model of the ship from the rudder command $\delta_r(t)$ to the true $\psi(t)$ and compass $\psi_m(t)$ headings takes the form shown in Fig. 1.

3.2 Linear Parameter-Varying Model

A linear parameter-varying (LPV) model is used in this work to consider the behavior of the ship at different speeds. It is built around the same structure of Fig. 1 but taking the ship parameters K_{IS} and T_S as a function of the forward speed of the ship $u_s(t)$. This speed depends on the power commanded to the ship's propulsion machine. For a given value of the RPM of the propeller's shaft, there is a maximum possible speed u_{max}. The actual forward speed of the ship $u_s(t)$ will reach this value after a certain time depending on the the inertia of the vessel and the rudder position, as shown in Fig. 2.

The modeling assumption considers that the parameters of the ship K_{IS} and T_S are known for a set of defined values of the forward speed $u_s(t)$. If $(K_{IS_i},\ T_{S_i})$ and $\left(K_{IS_{i+1}},\ T_{S_{i+1}}\right)$ are the identified values for, respectively, the speeds u_{s_i} and $u_{s_{i+1}}$, for a speed $u_{s_i} < u_s(t) < u_{s_{i+1}}$

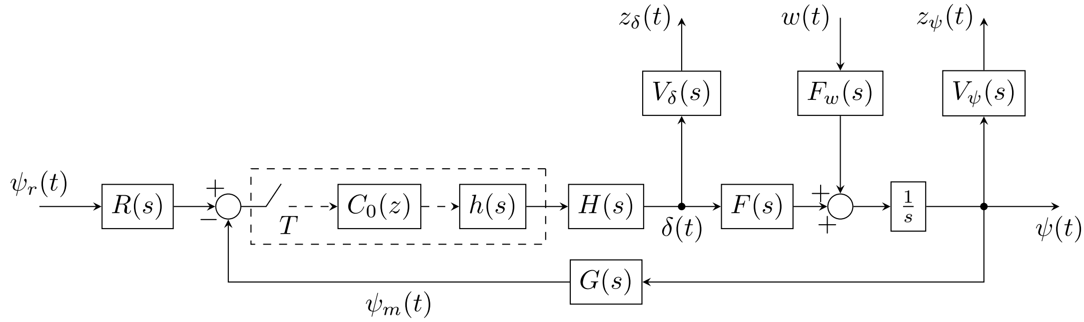

Fig. 3. Block diagram for the synthesis of the internal controller.

the instantaneous value of $K_{IS}(t)$ and $T_S(t)$ corresponds to a linear interpolation between the values at the extremes of the modeled interval.

4. CONTROLLER SYNTHESIS

A two-degrees-of-freedom (2-DoF) controller consists of two independent controllers in which a feedback part guarantees optimal rejection of stochastic disturbances while a feedforward part provides optimal trajectory tracking (Youla and Bongiorno, 1985; Grimble, 2001).

For the design of the 2-DoF controller, the same approach based on the PTF followed in Ladisch et al. (2004) is used. First, an internal controller is designed to guarantee an optimal rejection of disturbances introduced by the waves of the sea. We consider for that the block diagram in Fig. 3. The digital controller is represented by the series connection contained within the dashed box, consisting of a sampler, a discrete controller $C_0(z)$, and a zero order hold $h(s)$ converting the discrete control signal into a continuous one.

The blocks $H(s)$, $F(s)$, and $G(s)$ are the transfer functions already described in Section 3. The signal $w(t)$ is a zero mean Gaussian white noise process, which, together with the forming filter $F_w(s)$, is used to model the disturbances that the sea waves cause on the motion of the ship. The forming filter has the form

$$F_w(s) = \frac{2\omega_0 \lambda \sigma s}{s^2 + 2\omega_0 \lambda \sigma s + \omega_0^2}, \tag{8}$$

where the parameters ω_0, λ, and σ describe the characteristics of the sea based on an usual modeling approach using the Pierson-Moskowitz spectrum (Fossen, 2002).

The remaining blocks in Fig. 3 are needed for the definition of the optimization problem. The first one, $R(s)$, is a forming filter to obtain the reference signal with respect to which the system is to be optimized. Assuming that the input is a unit impulse, $\psi_r(t) = \delta(t)$, and that the step response of the system is to be optimized, $R(s) = \frac{1}{s}$ is taken.

Transfer functions $V_\psi(s)$ and $V_\delta(s)$ allow the designer to define the performance criteria to be used for the optimization. In the selection of the performance weights, the desired characteristics for the controller need to be carefully considered. One important aspect to take into account is that the only way to guarantee that the optimal controller includes a pure integral action, needed to obtain

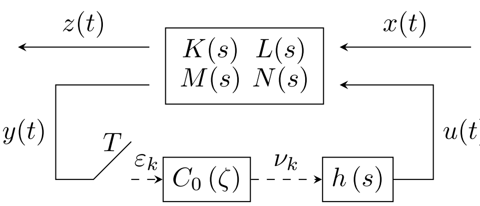

Fig. 4. Standard sampled-data system.

a zero steady state error in the step response, the weight of the output signal, $V_\psi(s)$, should contain a pole at the origin of the complex plane.

The quadratic error to be minimized is the total variance of the output signals $z_\psi(t)$ and $z_\delta(t)$,

$$J = \int_0^\infty z_\psi^2(t) + z_\delta^2(t) dt. \tag{9}$$

By employing the DLT, the integral (9) can be expressed in the frequency domain and discretized as

$$J = \frac{1}{j2\pi} \int_{-j\infty}^{j\infty} A(\zeta) W_d(\zeta) W_d(\zeta^{-1}) - B(\zeta) W_d(\zeta) \\ -B(\zeta^{-1}) W_d(\zeta^{-1}) + C(\zeta) ds, \tag{10}$$

where $\zeta = e^{-sT}$. How the coefficients $A(\zeta)$, $B(\zeta)$, $Z(\zeta)$ are related to the transfer functions of the individual elements in Fig. 3 is presented with all details by Rosenwasser and Lampe (2000). The most important point is that, in (10), $W_d(\zeta)$ is the only element that depends on the transfer function of the controller $C_0(z)$.

The process of obtaining the optimal transfer function $C_0(z)$ is also detailed by Rosenwasser and Lampe (2000) and it has been already implemented in the MATLAB toolbox DIRECTSD (Polyakov et al., 2006; Cepeda-Gomez and Lampe, 2015).

In order to use the DIRECTSD toolbox, the control system has to be transformed into the standard form for a sampled data system (Polyakov et al., 2006; Cepeda-Gomez and Lampe, 2015) which is seen in Fig. 4.

For this particular case, we have that $x(t) = [w(t)\ \psi_r(t)]^T$ and $z(t) = [z_u(t)\ z_\delta(t)]^T$, which leads to

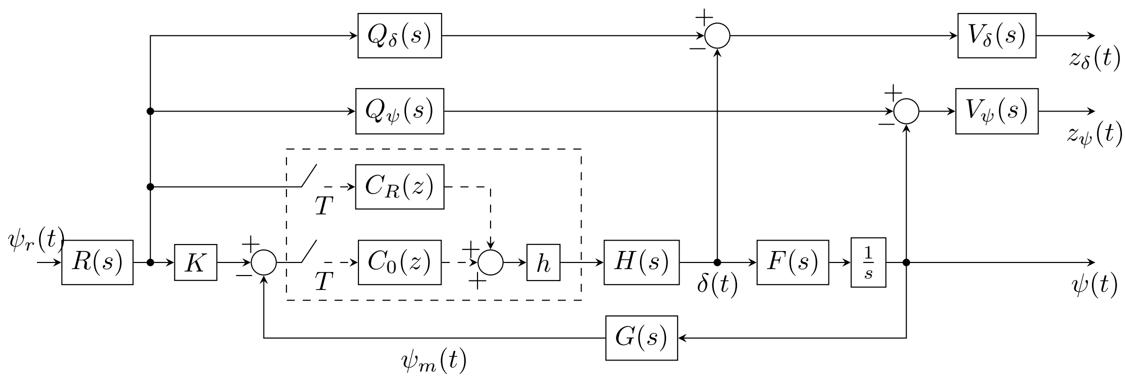

Fig. 5. Block diagram for the synthesis of the reference controller.

$$K(s) = \begin{bmatrix} \frac{1}{s}V_\psi(s)F_w(s) & 0 \\ 0 & 0 \end{bmatrix} \; L(s) = \begin{bmatrix} \frac{1}{s}V_\psi(s)F(s)H(s) \\ V_u(s)H(s) \end{bmatrix} \tag{11a}$$

$$M(s) = \begin{bmatrix} -\frac{1}{s}G(s)F_w(s) & R(s) \end{bmatrix} \; N(s) = -\frac{1}{s}G(s)F(s)H(s) \tag{11b}$$

The function `sdh2` in the DirectSD toolbox will accept as inputs the representation (11) as a linear system in any of the standard Matlab forms (tf, zpk, ss) together with sampling time and will produce the optimal internal controller $C_0(z)$.

Once the internal controller is known, the reference controller is designed following the structure presented in Fig. 5. In this diagram, $Q_\psi(s)$ and $Q_\delta(s)$ represent the ideal responses for the output of the system and the control action.

In this work, we consider the ideal trajectory to be generated by a continuous PD controller of the form $C(s) = K_p\left(1 + \frac{sT_D}{1+sT_{V1}}\right)$, which already includes a low-pass filter in the derivative element to make it implementable in real time. The criteria used to select the control gains are based on the concept of *good seamanship*, which is a qualitative evaluation of the movements of the ship as they would be performed by a skilled sailor. Several studies, *e.g.*, one from Lampe et al. (1998), present ways of translating these qualitative observations into measurable characteristics of the ship's time response.

The block K in Fig. 5 represents a static gain used to weigh the influence of the reference signal in the internal loop. This gives an extra level of freedom to the designer, and therefore it is spoken of a 2.5-DoF design when $K \neq 0$ (Grimble, 1994). For this work, we adopt the 2-DoF structure and consider $k = 0$.

The standard structure of Fig. 4 is updated to the form seen in Fig. 6. The objective is now to minimize the variance of the output signal $z(t)$, which has the same form as in (9). The use of the PTF approach allows to reduce this problem to the same functional (10), of course with different coefficients $A(\zeta)$, $B(\zeta)$, $Z(\zeta)$, as shown by Polyakov (2001). The transfer functions for this case are

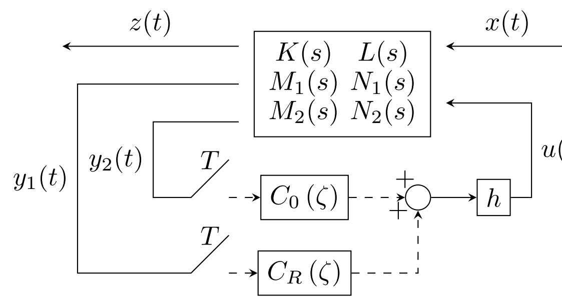

Fig. 6. Standard 2-DoF sampled-data system.

$$K(s) = \begin{bmatrix} -V_\psi(s)Q_\psi(s)R(s) \\ -V_\delta(s)Q_\delta(s)R(s) \end{bmatrix}, \tag{12a}$$

$$L(s) = \begin{bmatrix} \frac{1}{s}V_\psi(s)F(s)H(s) \\ V_u(s)H(s) \end{bmatrix} \tag{12b}$$

$$M_1(s) = R(s),\; M_2(s) = 0 \tag{12c}$$

$$N_1(s) = 0,\; N_2(s) = -\frac{1}{s}G(s)F(s)H(s) \tag{12d}$$

The function `sd2dof` in the DirectSD toolbox takes as inputs the representation (12) an the internal controller $C_0(z)$ to calculate the optimal reference controller $C_R(z)$.

5. SIMULATIONS

Parameters representative of a container ship of the type *Warnow CV 2500*, taken from the work of Ladisch (2004), were used for the numerical simulations. The values of these parameters are presented in Table 1. They represent the ship at five different values of the forward speed. The ship model is completed with time constants of the rudder $T_{rm} = 2\,\mathrm{s}$ and the giro compass $T_{rm} = 3\,\mathrm{s}$ A sample time $T = 2\,\mathrm{s}$ was used for the discrete controllers.

For the design of the internal optimal controller the design weights were selected as $V_u(s) = 10$ and $V_\psi(s) = \frac{1}{s}$, the latter to guarantee that an integral control action is included in the result. More elaborated filters can be used to weigh the output signals, but the price to pay for this would be an increased order of the resulting controllers. The parameters for the forming filter to represent the sea wave spectrum were selected as $\lambda = 0.3$, $\omega_0 = 0.3$, and $\sigma = 0.01$.

Table 1. Nomoto-Model Parameters for a Ship of the type *Warnow CV2500*

Level	RPM	Speed [Knots]	K_{IS} [rad]	T_S [s]
1	38	2	0.00694	182.1950
2	55	3.25	0.0113	112.12
3	78	5	0.0174	72.878
4	95	7.5	0.0260	48.5853
5	116	10	0.0347	36.4390

Table 2. Gains, Zeros, Poles, and Optimal Cost of the Feedback Controllers $C_{0_i}(z)$

	C_{0_1}	C_{0_2}	C_{0_3}	C_{0_4}	C_{0_5}
k_0	26.0322	19.0066	14.4255	11.1824	9.3446
z_1	0.9891	0.9823	0.9740	0.9669	0.9608
z_2	0.9852	0.9800	0.9729	0.9597	0.9466
z_3	0.5134	0.5134	0.5134	0.5134	0.5134
z_4	0.3679	0.3679	0.3679	0.3679	0.3679
p_1	-0.2534	-0.2533	-0.2533	-0.2532	-0.2530
p_2	1.0000	1.0000	1.0000	1.0000	1.0000
p_3	0.9336	0.9058	0.8702	0.8217	0.7714
p_4	0.5162	0.5190	0.5243	0.5349	0.5508
J	920.4944	579.8532	387.7667	268.2049	207.2391

With these values, the DirectSD toolbox produced five fourth-order controllers of the form $C_{0_i} = k_{0_i} \frac{\sum_{n=1}^{4}(1-z_{i_n} z^{-1})}{\sum_{n=1}^{4}(1-p_{i_n} z^{-1})}$, with the numeric values for the poles p_{i_n}, zeros z_{i_n}, and gains k_{0_i} presented in Table 2. The table also shows the quadratic cost obtained by each controller. Note that all controllers include the integral action (a pole at $z = 1$) induced by the selection of the weight $V_\psi(s)$.

For the ideal trajectory generation, the gains of the *PD* controllers were selected depending on the model of the ship at each speed based on the *good seamanship* considerations. The weights for the output signals, $V_\psi = 1000$ and $V_\delta = 1$, were selected to emphasize good trajectory tracking to the cost of higher control energy.

The ideal continuous response increases the order of the dynamics in (12) and this is reflected in a relative high (11$^{\text{th}}$) order for the optimal reference controllers. Due to space constraints, the numeric values defining the controllers are presented only for three controllers (C_{R_1}, C_{R_3}, and C_{R_5}) in Table 3.

Something important to notice is that the effect of the reference controller on the quadratic cost of each system. While for the fifth controller there is a reduction of almost one order of magnitude, the cost for the controller for the lowest speed level is increased by a factor of more than 10. This could be explained by the fact that the PD controller was first tuned to the highest speed case ($v_s(t) = 10$ kn) and the gains adapted to lower speeds. A proper design of the reference trajectory for each case should allow a generation of a more appropriate controller, which would lead to better reduction in cost.

The results of a simulation run are presented in Fig. 7, Fig. 8, and Fig. 9. A maneuver consisting on several linear variations of heading while the ship accelerates through the different speed levels causing the controllers to switch

Table 3. Gains, Zeros, Poles, and Optimal Cost of some of the Reference Controllers $C_{R_i}(z)$

	C_{R_1}	C_{R_3}	C_{R_5}
k_R	706.9021	119.6876	31.6943
z_1	0.9891	0.9729	$0.9499 + j0.0705$
z_2	$0.9838 + j0.0260$	$0.9693 + j0.0464$	$0.9499 - j0.0705$
z_3	$0.9838 - j0.0260$	$0.9693 - j0.0464$	0.9466
z_4	0.9687	0.9424	0.9086
z_5	$0.7292 + j0.2037$	0.5134	0.5134
z_6	$0.7292 - j0.2037$	0.5103	0.5124
z_7	0.5134	$0.3966 + j0.3115$	0.3679
z_8	0.5088	$0.3966 - j0.3115$	$0.0658 + j0.2822$
z_9	0.3679	0.3679	$0.0658 - j0.2822$
z_{10}	-0.2534	-0.2534	-0.2534
z_{11}	-0.1205	-0.1067	-0.0624
p_1	1.0000	1.0000	1.0000
p_2	0.9336	0.8702	$0.7900 + j0.0629$
p_3	$0.7900 + j0.0629$	$0.7900 + j0.0641$	$0.7900 - j0.0629$
p_4	$0.7900 - j0.0629$	$0.7900 - j0.0641$	0.7714
p_5	$0.7301 + j0.2068$	0.5243	0.5508
p_6	$0.7301 - j0.2068$	$0.3859 + j0.3194$	0.2820
p_7	0.5162	$0.3859 - j0.3194$	-0.2810
p_8	0.2820	0.2818	-0.2530
p_9	-0.2535	-0.2550	$0.0468 + j0.2443$
p_{10}	-0.2534	-0.2533	$0.0468 - j0.2443$
p_{11}	0.1443	0.1444	0.1443
J	13100	396.99	39.745

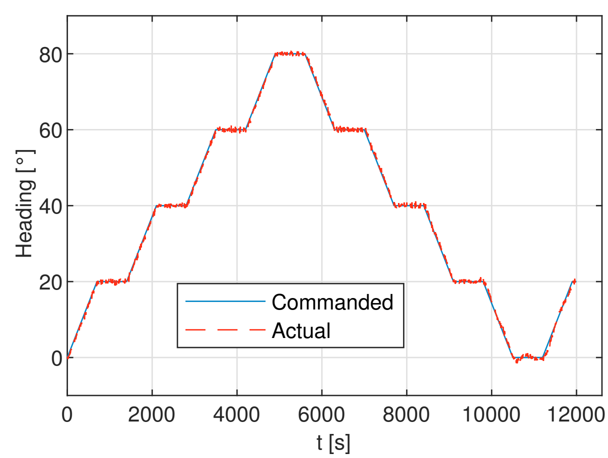

Fig. 7. Commanded ($\psi_r(t)$) and actual ($\psi(t)$) heading angle during the simulation.

was performed. It can be observed in Fig. 7 that, even in the presence of disturbances, a qualitative good heading tracking behavior is obtained.

Figure 9 shows the variation of the rudder angle. The largest deviations are in general observed at low speeds and big swings correlate with the variations on the command signal. No extreme excursions are associated with the switching of the active controller, which occurs when the speed presented in Fig. 8 moves to a new level.

6. CONCLUSION

This paper studies the feasibility of a switched adaptive scheme for heading control of a ship. A simplified scheduling rule is applied in which one controller is selected out of a pool of five optimal controllers based on the forward speed of the ship. Each of the individual controllers con-

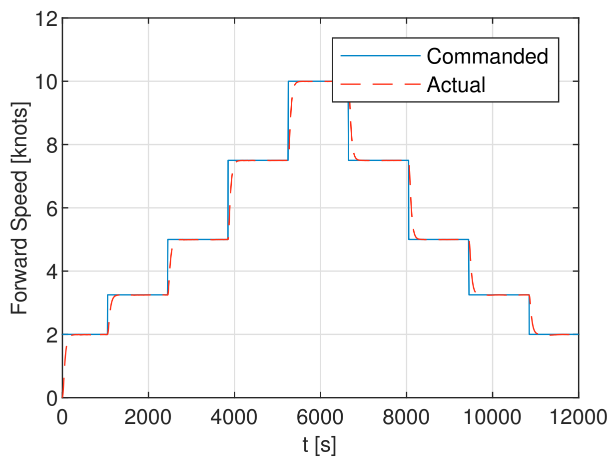

Fig. 8. Commanded and actual forward speed of the ship.

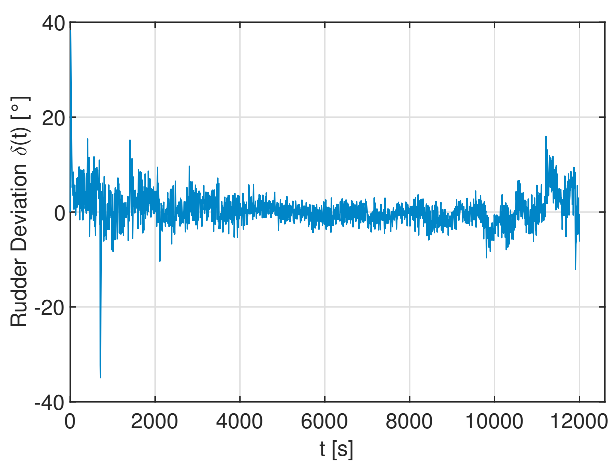

Fig. 9. Rudder deviation angle $\delta(t)$.

sists of a 2-DoF optimal digital controller synthesized using the parametric transfer function approach for the analysis of sampled-data systems.

By means of numerical simulations, the proposed switched controller was tested with a speed dependent, LPV model of a container ship. The simulations show that the concept works, providing proper tracking responses.

The smoothness of the control action during the switching from one controller to the next seems to be affected by the relative distance in the space of the scheduling parameter between the operating point for which each controller is optimized. Exploring this effect is the main direction for future studies in this topic.

Both the code of the examples and the DirectSD toolbox are available for free and can be requested via email to the authors.

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