UDC 2.10. /2.3

ADAPTIVE SYSTEM FOR STEERING A SHIP ALONG A DESIRED ROUTE

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Annotation

An adaptive ship steering system along a preset track is an example of an intelligent system. An optimal linear quadratic regulator (LQR) regulator with a symmetric indicator of control quality was adopted as the control algorithm. The model identification was based on the continuous version of the least squares method. A significant part of the article presents the proof of the stability of the proposed system. The results of the calculation experiments are provided to confirm the effective and correct working of the system.

Introduction

The design of a control system is usually based on a mathematical model of the object as the basis for the synthesis. In reality, the determination of the exact structure of the model and values of its parameters is not an easy task. The parameters may change in time under the influence of the properties of the object itself or as a result of changing environmental conditions. This entails the need to create adaptive control algorithms, which are characterized by learning capacity, a large range of autonomy in responding to changes in the system and the ability to perform in complex conditions. Algorithms of this type are the essence of intelligent control systems.

An example of the above problem is the steering of a ship, a complex dynamic object subject to strong disturbances. The scope and sensitivity of the steering panel operation changes as sailing conditions change (ship speed, water depth, wind force, current, waves, loading condition, etc.), but a skilled helmsman is able to allow for the changes and perform as instructed. Changing conditions, however, create great difficulties in designing autopilots because a well-designed autopilot, to perform a control task, will have to change its parameters in time based on the identified parameters of the model or even make use of the variable structure of the model.

One of the classic problems in this field is automatic ship steering along a preset route, generally defined in the form of a broken line, joining a series of preset waypoints. The ship's track-keeping ability is crucial, because improper control of the rudder results in the reduction of the average speed, longer track and time of the voyage and, consequently, higher fuel consumption, leading to higher total operating costs. The associated operational problem is steering gear overload, which may lead to a critical breakdown. Most importantly, uncontrollable yawing, especially on waterways with increased traffic, adversely affects the level of safety, increasing the risk of collision (Guze, et. al., 2016)

The proposed solution effectively stabilized the ship's trajectory relative to the desired track, and the whole process ran in the online mode. This is important for the implementation of the developed system. Implementation often seems to be very difficult in the cases presented in the literature on the subject. This limitation is a consequence of the assumptions made in these methods. The proposed adaptive algorithm for the automatic track-keeping of a ship is a functional solution, characterized by the high control quality combined with the possibility of effective implementation in marine navigational systems.

Calculation Experiments

The experiments were made in the Matlab/Simulink environment. A de Witt–Oppe model (1984) was used as an object (vessel), incorporating the dynamics of the steering gear (Fossen, T.I., 1994):

$$
\begin{aligned}
\dot{x}_1 &= x_5 \cos x_3 - x_6 \sin x_3 \\
\dot{x}_2 &= x_5 \sin x_3 + x_6 \cos x_3 \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= -a_1 x_4 - a_2 {x_4}^3 + a_3 u \\
\dot{x}_5 &= -f x_5 - W {x_4}^2 + S \\
x_6 &= -r_1 x_4 - r_3 {x_4}^3 \\
\dot{u} &= u_z - u \\
|u_z| &\leq u_{\max} \\
|\dot{u}| &\leq \dot{u}_{\max}
\end{aligned}
$$

where

$(x_1, x_2) = (x, y)$—Cartesian coordinates (ship's position),
$x_3 = \psi$—deviation from the course,
$x_4 = r$—angular velocity,
x_5—longitudinal speed,
x_6—lateral speed,
$u = \delta$—rudder angle,
$u_z = \delta_z$—preset rudder angle,
$\delta_{\max}$—maximum rudder angle,
$\dot{\delta}_{\max}$—maximum rate of turn of the rudder,
S—propeller thrust,
a_1, a_2, a_3, f, W, r_1, r_3—coefficients determined from model tests (different for different types of vessels).

The ship movement parameters assumed here are those of a ship of mariner class, such as the m.s. Compass Island (Wit, C.; Oppe, J.,1984): a1 = 0.018(1/s), a2 = 37.2(s/rad2), a3 = 0.001(1/s2), f = 0.014(1/s), w = 124(m/rad2), s = 0.11(m/s2), r1 = −69.5(m/rad), r3 = 0(m•s2/rad3). The selected ship has the following characteristics: gross registered tons 9214 (t), 13498 DWT (Dead Weight Tonnage) (t), single screw, length 172 (m), maximum draft 8 (m), maximum speed 20 (knots), maximum (minimum) angular velocity rmax = 0.0191(rad/s) (rmin = −0.0191(rad/s)), maximum (minimum) rudder angle δ.max = 0.6(rad) (δmin = −0.6(rad)), maximum (minimum) rate of turn of the rudder δmax = 0.066(rad/s) (δmin = −0.066(rad/s)).

In order to take account of disturbances, the simulations included a signal characteristic of wind-induced sea waves (the wind direction conforms with the direction of the Y axis) (Fossen, T.I., 1994).

The established initial parameters of the simulation were as follows: angular velocity r = 0 (rad/s), deviation from the course ψ = 0 (rad), rudder angle δ = 0 (rad), ship's speed v = 7.7 (m/s), and ship's position (0, −500)(m). The time span of the simulation was determined at 1000 (s).

The track to be followed by the ship was determined by setting the waypoints P1(0, 0), P2(3000, 0), P3(3000, 1000), and P4(10, 000, 1000)(m).

The calculation experiments were conducted to compare the performance of the proposed adaptive system and the LQR regulator without the identification of the model parameters. The values λy = 1/2000, λψ = 1, λδ = 5, R = 500 (m) were arbitrarily accepted as the LQR regulator parameters. Figure 3 shows an example simulation result for the case where the initial estimates of the Nomoto model parameters assumed the values a0 = 0.02 (1/s) and c0 = 0.002 (1/s2) (nominal values a = 0.018(1/s), c = 0.001(1/ s2)). Preliminary estimates of the Nomoto model parameters were used for the determination of the LQR regulator's gain and as input data for the adaptive algorithm. The charts illustrate, respectively, the simulation results: ship movement trajectory, control quality indicator, rudder angle, and deviation from the course. It can be observed that both the control by the proposed method and by LQR lead to the ship correctly stabilizing its position relative to the planned track. However, the proposed method had a significantly higher control quality. This applies to the value of the control quality indicator (lower for the proposed method) and to oscillations and overshoots (lower in the proposed method). It should be noted that the oscillation of the presented system (the lower left chart) can depend on the parameters λy, λψ, λδ, which is interpreted as a compromise between the deviation from the route and the rudder angle (steering gear load). The automatic selection of these parameters goes beyond the framework of this work and will be examined in the future.

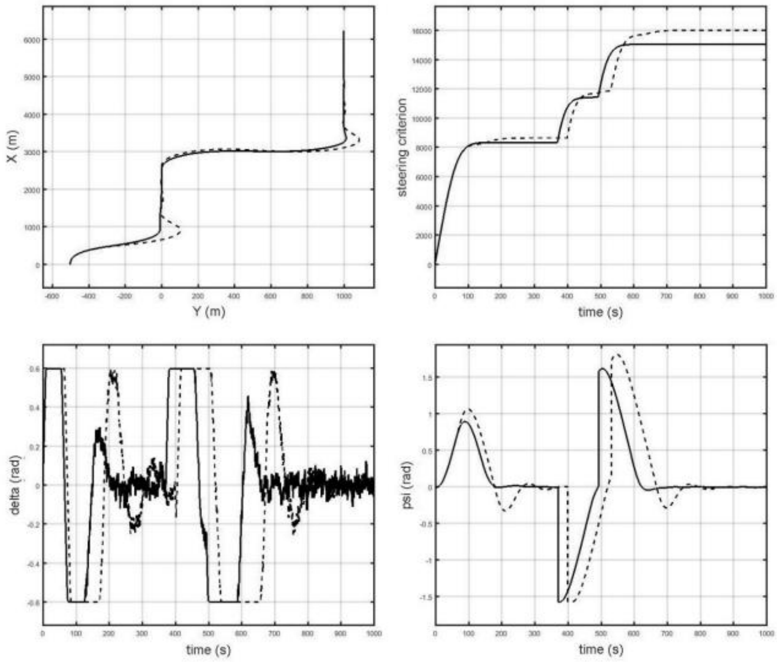

Figure 1. An example outcome of the comparison of the proposed adaptive system (continuous line) and linear quadratic regulator (LQR) regulator without model parameter identification (dashed lined).

The situation presented in the experiment is typical of this kind of research. In all cases considered, the value of the quality indicator for the ship controlled by the proposed adaptive system was lower than in the case of the LQR regulator without the identification of the model parameters. The method led to a reduction of the control quality indicator value to 15%, depending on the assumed initial estimates of the Nomoto model parameters.

Conclusions

The article presented an adaptive control system for keeping track of a ship as an element of an intelligent system applicable in modern marine navigation. (Borkowski, P., 2017) An optimal LQR regulator with a symmetric indicator of control quality was adopted as the control algorithm. The model identification was based on the continuous version of the least squares method.

The results of calculation experiments clearly confirmed the high quality of control of the proposed adaptive system. This refers to the minimization of the control criterion values as well as the reduction of oscillation and overshoot. In all examined cases, the control quality of the proposed system was higher than that of the LQR regulator without the identification of the model parameters.

The proposed solution effectively stabilized the ship's trajectory relative to the desired track, and the whole process ran in the online mode. The simplicity of the method and the lack of application limitations are relevant for the implementation of the developed system on vessels. The proposed adaptive algorithm for automatic track-keeping by a ship is a functional solution, characterized by high control quality that can be effectively implemented in navigational systems.

Literature

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