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Adaptive dynamic control allocation for dynamic positioning of marine vessel based on backstepping method and sequential quadratic programming

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ABSTRACT

It is generally assumed in dynamic positioning of over-actuated marine vessels that the control effectiveness matrix (input matrix) is known and constant, or, in case of fault information, it is estimated by the fault detection and diagnosis system. The purpose of the study is to develop the adaptive dynamic positioning control system for an over-actuated marine vessel in the presence of uncertainties and with emphasis on limited information about thruster forces. The proposed approach bases on the MIMO adaptive backstepping method to design the high-level control law and then to give inputs to the control allocation unit. An adaptive solution allows to accommodate the unknown time-varying control effectiveness matrix and to update the thrust distribution due to actuator losses and failures. The effectiveness and correctness of the proposed control schema is demonstrated by simulations involving a redundant set of actuators when some of them have lost partially their efficiency or failed. The evaluation criteria include energy consumption, robustness and accuracy of dynamic positioning during typical vessel operations. Based on simulation tests results, the generated control inputs stabilize the ship position and orientation violated by thruster faults.

1. Introduction

Ship motion control at low speed includes dynamic positioning (DP), the main goal of which is to maintain ship position and heading in the presence of environmental disturbances. This task is performed through ship motion control in three degrees of freedom, using active thrusters and propellers which can generate forces and moments in different directions of motion. A survey of selected major research and technology advances in the field of dynamic positioning is summarized in (Sorensen, 2011). In the DP system, actuator settings are determined based on the signal passed from the DP-controller (high-level controller) and the control allocation system. The DP controller controls three degrees of freedom of ship motion, which are: sway, surge, and yaw motion. Based on the information on these motion components, it generates the set values of forces and moment for the control allocation (CA) system. In the CA system, the vector of forces and moment is distributed into actuators and transformed to signals controlling actuator settings, i.e., rotational speeds of main propulsion propellers, and azimuthal and tunnel rudders, rudder deflection angles, adjustable propeller blades. In modern DP vessels, the total number of control inputs exceeds the total number of controlled degrees of freedom, so the type of over-actuated control takes place. The exact number of control inputs may differ depending on tasks performed by the DP ship, DP Classes, ship size and economic conditions. The CA system takes into account physical constraints of rudder and propulsion operation, (e.g. input saturation and rate constraints), steering and propulsion efficiency, configuration, as well as constraints resulting from current amount of electric and mechanical power available on the ship. A solution is searched which will allow to obtain minimal energy losses and wear of actuators when executing the basic goal of control, which is precise ship positioning.

A detailed overview of the existing control allocation methods can be found in (Bodson, 2002; Johansen and Fossen, 2013). The control allocation problem is mostly viewed as a static or quasi-dynamic optimization problem that is solved independently of the dynamic control problem considering non-adaptive linear effector models and neglecting the actuator dynamics. The simplest of the presented solutions consist in calculating a pseudo-inverse matrix and the use of classical optimization methods, such as the Lagrange method or the least square method to minimise the activity of the actuators. More complicated solutions consist of numerous optimization methods to take into account constraints connected with saturation of actuators: penalty

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function (Bodson, 2002), direct allocation (DA) method, redistributed pseudo-inverse (RPI) method (Oppenheimer et al., 2006), cascading generalized inverse (CGI) (Lindegaard and Fossen, 2003). The linear actuator dynamics is considered by using model predictive control allocation (MPCA) (Hanger et al., 2011; Luo et al. 2004, 2007; Oppenheimer et al., 2004).

However, control allocation (CA) algorithms do not usually provide robustness to uncertainties in the control effectiveness matrix, which is of basic importance for practical applications especially during actuator failure. The uncertainties result from actuator configuration and thrust losses, which depend on environmental conditions, water density, ship velocity and actuator faults. It is generally assumed for a DP vessel that the control effectiveness matrix (input matrix) is known and constant, without any regard how the control effectiveness matrix will change in time, states and inputs. In the case of actuator fault information, the control effectiveness matrix is usually estimated by the Fault Detection and Diagnosis (FDD) systems, which are strongly committed to the fault-tolerant control strategy. Fault-tolerant (FT) approaches addressed to DP control system have been recently proposed by Benetazzo et al. (2015), Lin and Du (2016), Zhang and Yang (2017), Su et al. (2017). The disadvantage of these approaches is that they require the fault detection and isolation mechanism to be included directly in the control law formulation.

Another way to reduce the effect of thrust losses is using adaptive dynamic control allocation strategy. This approach to designing DP systems was presented in the literature by Tjønnås and Johansen (2005, 2007, 2008). In those papers, instead of optimizing the control allocation at each time instant, a dynamic approach was considered by constructing update-laws that represent asymptotically optimal allocation search and adaptation formulated based on the Lagrangian function and the Lyapunov theory.

This paper presents a design of adaptive dynamic control allocation for an over-actuated dynamic positioning vessel based on the adaptive vectorial backstepping (Krstíc et al., 1995) and sequential quadratic programming (Johansen and Fossen, 2013) as an alternative formulation to accommodate to thrust uncertainties. In our paper the control allocation problem is considered with respect to uncertainty in the control effectiveness matrix as a function of operating point variables. Backstepping was a widely applied for marine vessels (Cheng-Du et al., 2013; Fossen, 2000; Tsopelakos and Papadopoulos, 2017; Witkowska and Śmierzchalski, 2012; Witkowska, 2013) to ensure the closed loop system to be uniformly ultimately bounded (UUB). Compared to conventional methods, such as linearization (Bańka et al., 2013), LQG, sliding mode control (Tomera, 2010; Tannuri et al., 2010), robust H∞ control (Katebi et al., 1997), fuzzy logic (Cao et al., 2001), and neural nets (Cao et al., 2000), the vectorial adaptive backstepping gives an effective and structured design procedure in a recursive way, which, however, requires very complex computations. Among other factors, this complexity results from repeated analytical calculations of the time derivative of virtual control inputs ("explosion of terms") (Swaroop et al., 2000; Mingyu et al., 2016) and the accurate knowledge of the regression matrices (Du et al., 2015; Xia et al., 2016). Attempts to use the backstepping algorithm in practical application gave rise to the problems of high output energy and difficult cancellation of nonlinear function, which were analysed by (Zhang et al., 2018) for ship course keeping control. There are a few methods to simplify the standard backstepping procedure by differentiation of the virtual control law (e.q. Lyapunov redesign method, tracking differentiators (TD), dynamic surface control (DSC), and other filtering methods) (Wang and Shirinzadeh, 2014; Wang and Wang, 2015). However, these methods have many limitations, despite their simplicity of application. A systematic method to choose appropriate gains and filter time constants for a dynamic surface controller has not been fully addressed yet in the literature. Similarly, the order of the differentiator TD should also be carefully selected when the estimated disturbances can be directly applied in the backstepping controller. Most of the papers which aimed at designing DP controllers with the above methods did not take into account the dynamics of the actuators. Although designed based on standard vectorial adaptive backstepping procedure and sequential quadratic programming, the DP control system proposed in the article has not yet been dealt exactly with in such form. First, the high-level motion control based backstepping algorithm is developed to update the commanded forces and moment in the presence of the unknown: control effectiveness matrix, ship dynamics model parameters, and environmental disturbances. Furthermore, the control allocation based sequential quadratic programming was used for actuator-force mapping, to divide the updated commanded forces and moment into particular commanded settings of actuators, and to compensate total actuator faults. The relevant element of this structure is a detailed algorithm to estimate the control effectiveness matrix for the proposed DP control system without a priori knowledge of vessel's model parameters and slowly varying disturbances. Additionally, the linear time-varying actuator dynamics is taken directly into control law formulation. We are also providing some modification when using standard backstepping designing procedure. The regression matrix is determined not directly in the ship dynamics model, but only at the stage of creating the Lyapunov function, which significantly simplifies the control law designing procedure. Next, the proposed procedure has ability to accommodate the unknown time-varying control effectiveness matrix and to update the thrust distribution due to actuator losses and partial faults. Additionally, it provides robustness in control allocation with respect to uncertainties in the control input matrix as a function of operating point variables.

The effectiveness and correctness of the proposed control schema is demonstrated in simulations involving a redundant set of actuators, when some of them have lost partially their efficiency or failed. The evaluation criteria include energy consumption, robustness and accuracy of dynamic positioning during typical vessel operation. Thorough comparisons were made between CGI, WLS (Weighted Least Square) and MLS (Minimal Least Squares) algorithms to obtain the best performance of the optimization process. Simulation tests reveal correct operation of the system, high accuracy of control, and convergence to the set values. The results of simulation tests testify to good stability of system operation within the analysed range of operation points referring to real manoeuvring situations.

2. System description and problem statement

2.1. Ship dynamics and kinematics

For low speed applications, during station-keeping of the surface vessel it is convenient to consider the low frequency (LF) mathematical model in surge, sway and yaw, which is dynamically linear and kinematically nonlinear, according to (1)–(2) (Fossen, 2011). In this model, the pitch and roll angles are assumed small, the ship has port-starboard symmetry, the Coriolis and centripetal terms are negligible, and the linear part of the damping matrix caused by wave drift damping and laminar skin friction is dominating.

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\mathbf{v} \tag{1}$$

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{D}(\mathbf{v} - \mathbf{v}_c) = \boldsymbol{\tau} + \boldsymbol{\tau}_{env} \tag{2}$$

The output vector $\boldsymbol{\eta} = [x,y,\psi]^{\mathrm{T}} \in \mathrm{R}^{3\times1}$ consists of ship's position (x,y) and heading $\psi \in [-\pi, \pi]$ in the earth-fixed frame, the vector $\mathbf{v} = [u, v, r]^{\mathrm{T}} \in \mathrm{R}^{3\times1}$ denotes the ship's forward, lateral and angular speeds in the body-fixed frame, respectively, $\mathbf{v_c} = [u_c, v_c, 0]^{\mathrm{T}} \in \mathrm{R}^{3\times1}$ is a vector of current velocities, $u_c = V_c \cos(\beta_c - \psi)$, $v_c = V_c sin(\beta_c - \psi)$. In computer simulations and low speed applications, the average current velocity V_c and direction β_c can be generated by random walk process (Fossen, 1994). The input vector $\boldsymbol{\tau} = [\tau_x, \tau_y, \tau_n]^{\mathrm{T}} \in \mathrm{R}^{3\times1}$ represents the generalized forces and moment coming from the thrusters and propulsion devices (actuators) in the body-fixed frame, and the vector