Ocean Engineering 160 (2018) 1–9

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Fault tolerant model predictive control for an over-actuated vessel

Luca Cavanini *, Gianluca Ippoliti

Università Politecnica delle Marche, Dipartimento di Ingegneria dell'Informazione, Via Brecce Bianche 12, 60131, Ancona, Italy

ARTICLE INFO

Keywords:
Model predictive control
Thrust allocation
Fault tolerance
Linear parameter-varying model

ABSTRACT

This paper presents a Fault Tolerant-Model Predictive Control (FT-MPC) for a vessel featured by the presence of a greater number of actuators with respect to the number of controlled outputs, classified in the category of over-actuated systems. Over-actuated plants are usually controlled by a main controller in conjunction with a Thrust Allocation (TA) algorithm in order to guarantee the required control performances. In this work an unconstrained Quadratic Programming (QP) TA policy is considered in conjunction with a MPC to drive the vessel. The proposed solution has been tested on an over-actuated vessel called Cybership II. The main contribution of this paper is the introduction in the MPC of a fault tolerant action, in order to improve control performance in actuators' fault scenarios. A Linear Parameter-Varying (LPV) model has been used to described the Cybership II dynamics and to develop the proposed controller. Considering this model, a MPC has been developed to drive the vessel, verifying controller performance in standard control scenarios. The proposed FT-MPC has been compared with respect to a standard MPC in actuators' fault scenarios, considering several wave noise disturbances. Reported simulation results show the effectiveness of the proposed approach.

1. Introduction

A Fault Tolerant Control System (FTCS) is a closed loop controller able to automatically accommodate component failures, maintaining system stability and acceptable control performance in the event of fault (Zhang and Jiang, 2008). Research and development of FTCS and Fault Detection and Diagnosis (FDD) systems involved large part of the international research community, due to a growing demand for safety, reliability, maintainability, and survivability in dynamical systems (Patton, 2015). The FDD systems detect if there is a fault in the system and provide some specific information about it (Yin et al., 2014a). On the other hand, the FTCS is designed to use information provided by the FDD to re-modulate the controller depending on the availability of redundancies in the control system as well as design approaches used in the synthesis of fault-tolerant controllers (Jiang and Yu, 2012). Different FTCS solutions have been proposed for safety critical applications in several technical fields, such as power systems (Zhang et al., 2014), green energy production (Qiao and Lu, 2015) and Surface Vehicles (SVs) (Izadi-Zamanabadi and Blanke, 1999). Among the techniques proposed in the development of FTCS, adaptive control (Maalouf et al., 2015), fuzzy-based policy (Tong et al., 2014) and most recently data-driven approach (Yin et al., 2014b) represent the widely used solutions due to their typical on-line re-modulation features.

During the past few years Model Predictive Control (MPC) became increasingly interesting in several fields (e.g. automotive, SVs and power converters (Pisaturo et al., 2015; Oh and Sun, 2010; Cavanini et al., 2016; Cavanini et al., 2017a)) and has been also proposed in conjunction with FFD techniques in order to develop FT controllers (Sanchez et al., 2016; Peng et al., 2016). MPC explicitly uses the system model to formulate and solve at each sampling time a constrained, finite-horizon, optimal control problem allowing to optimally drive multivariable systems (Camacho and Alba, 2013). In this paper a Fault Tolerant (FT) MPC policy has been proposed to drive an over-actuated vessel. The considered plant is the Cybership II (Skjetne et al., 2004), a scale model of a vessel provided with a redundant set of actuators. For this reason it requires a low level Thrust Allocation (TA) algorithm in order to obtain prescribed closed loop control performance by an optimal control force allocation among available actuators. The introduction of TA policies is a standard solution to simplify the design of control system for over-actuated system and it is usually considered to develop FTCS (Wu et al., 2016).

The main contributions of this paper is the introduction of a feedback loop between the TA algorithm and the MPC, in order to model actuators' fault or failure and to automatically re-modulate the fault-free control law by the introduction of the fault effect into the MPC reference model. Due to the considered feedback, the proposed FT-MPC allows to improve control performances in actuators' fault scenarios and guaranteeing

* Corresponding author.
E-mail addresses: l.cavanini@univpm.it (L. Cavanini), g.ippoliti@univpm.it (G. Ippoliti).

https://doi.org/10.1016/j.oceaneng.2018.04.045
Received 19 May 2017; Received in revised form 19 March 2018; Accepted 15 April 2018

system safety in case of critical faults combinations.

The proposed solution has been tested in different actuators' failure scenarios, comparing the obtained control results with respect to the performances of a standard MPC. The comparison has been done by the analysis of a standard control index and showing the transient response improvement in the reported results. Due to the presence of the wave disturbances, in real cases the control performance can be effected by the presence of output additive noise (Liu et al., 2017; Gao et al). In order to verify the control performance also in case of strong additive noise, comparison results varying the intensity of the additive output wave disturbances have been reported. To develop the proposed controller, a Linear Parameter-Varying (LPV) model of the vessel nonlinear dynamics has beed considered and a comparative analysis of the performance of the proposed LPV model-based MPC with respect to a standard nonlinear MPC has been performed.

The paper is organized as follow. In Section 2 the considered vessel dynamical model is presented, reporting the nonlinear plant characteristics and the LPV model. Section 3 deals with the considered TA and MPC policies. Section 4 presents the proposed FT-MPC solution. Section 5 reports the results of the simulations, comparing the considered control algorithm in several control scenarios. Section 6 concludes the paper.

2. Cybership II

In this section the Cybership II model considered in the control law formulation has been reported. In Subsection 2.1 the nonlinear vessel dynamic is presented, with the considered hypothesis in the model formulation. In Subsection 2.2 the Linear Parameter Varying (LPV) model of the vessel is given.

2.1. Dynamical system

The Cybership II (Skjetne et al., 2004) is a scale (1:70) model of an over-actuated supply vessel having a mass of 23.8 kg, a length of 1.255 m, a breadth of 0.29 m. The ship has two main propellers, two rudders aft and one bow thruster. The dynamic model is fully described by six degree-of-freedom (DOF) related to the ship position in the three-dimensional space (x, y and z positions called surge, sway, and heave, respectively) and orientation (ϕ, θ and ψ angles called roll, pitch and yaw, respectively). In the following the ship has been considered longitudinally and laterally metacentrically stable due to the assumption of small amplitude of roll and pitch angles and angle rate, i.e. $\phi = \theta = \Delta\phi = \Delta\theta \approx 0$. In the same way it is possible to discard the heavy dynamic considering the ship floating to $z \approx 0$. The result of the previous assumptions is that the Cybership II model is described by a 3 DOF equation system related to the state array $\eta = [x, y, \psi]'$ referred to the North-East-Down (NED) earth-fixed reference frame (Lindegaard and Fossen, 2003). Considering $\upsilon = [u, v, r]'$, with u and v the surge and sway velocities and r the yaw rate, the ship rigid body dynamic is described by the kinematic relationship:

$$\dot{\eta} = R(\psi)\upsilon \tag{1}$$

where $R(\psi)$ is the rotation matrix defined as:

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

As proposed in (Lindegaard and Fossen, 2003) the ship can be considered a low-speed surface vessel, described by:

$$\begin{aligned} \dot{\eta} &= R(\psi)\upsilon \\ M\dot{\upsilon} &= -D\upsilon + \overline{u} \end{aligned} \tag{3}$$

with $\overline{u} = [\tau_X, \tau_Y, \tau_N]'$ the input vector, where τ_X and τ_Y are the surge and sway control forces, respectively, τ_N is the yaw control moment and M, D are the mass and damping matrices, respectively:

$$\begin{aligned} M &= \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} \\ 0 & x_g - Y_{\dot{r}} & I_z - N_{\dot{r}} \end{bmatrix}, \\ D &= \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -Y_r & -N_r \end{bmatrix} \end{aligned} \tag{4}$$

The Cybership II dynamical model parameters have been reported in Table 1.

2.2. Linear Parameter Varying model

A Linear Parameter Varying (LPV) model of the nonlinear vessel dynamics of Eq. (2.1) has been considered. The discrete time LPV model $\mathscr{S}_k$ has the form

$$\begin{aligned} \overline{x}(k+1) &= A(\gamma_k)\overline{x}(k) + B(\gamma_k)\overline{u}(k) \\ \overline{z}(k) &= C(\gamma_k)\overline{x}(k) \end{aligned} \tag{5}$$

where $\overline{u}(k) = [\tau_X(k), \tau_Y(k), \tau_N(k)]'$ is the input vector of dimension $n_{\overline{u}} = 3$, $\overline{z}(k) = [x(k), y(k), \psi(k)]'$ is the output vector of dimension $n_{\overline{z}} = 3$, $\gamma_k \in \Gamma \subset \mathbb{R}^{n_\gamma}$ is the vector of the time-varying scheduling parameters of dimension $n_\gamma = 2$ and Γ is a given set of interest. The state vector $\overline{x}(k) = [\upsilon(k), \eta(k)]'$ has dimension $n_{\overline{x}} = 6$ and the sample time is $T_s = 0.25$ s. The system of Eq. (2.2) allows to represent the nonlinear model state evolution of Eq. (2.1) by a linear time-varying system described by the instantaneous value of the parameter vector defined as $\gamma_k = [\gamma_{1,k}, \gamma_{2,k}]'$, with $\gamma_{1,k} = \sin(\psi_k)$ and $\gamma_{2,k} = \cos(\psi_k)$, $\gamma_{1,k}, \gamma_{2,k} \in (-1, 1)$, such that

$$\begin{aligned} A(\gamma_k) &= A_k = e^{A(\gamma(t))T_s}, \\ B(\gamma_k) &= B_k = \int_0^{T_s} e^{A(\gamma(t))T_s} B d\tau \ , \ C(\gamma_k) = C_k = C. \end{aligned} \tag{6}$$

In Eq. (6), $A_k \in \mathbb{R}^{n_{\overline{x}} \times n_{\overline{x}}}$, $B_k \in \mathbb{R}^{n_{\overline{x}} \times n_{\overline{u}}}$ and $C_k \in \mathbb{R}^{n_{\overline{z}} \times n_{\overline{x}}}$ are the discrete time matrices of the LPV model obtained from the nonlinear model matrices of the vessel presented in Eq. (3), T_s is the sampling time and $A(\gamma(t)), B, C$ are the continuous time matrices describing the continuous time LPV model

$$A(\gamma(t)) = \begin{bmatrix} -M^{-1}D & 0 \\ R(\gamma(t)) & 0 \end{bmatrix}, \quad B = \begin{bmatrix} M^{-1} \\ 0 \end{bmatrix}, \ C = [0 \quad I] \tag{7}$$

with $I, 0 \in \mathbb{R}^{3\times 3}$ and M^{-1} is the inverse matrix of M, such that $M^{-1}M = I$.

3. Control architecture

The architecture of the controller is shown in Fig. 1. It is composed of a thrust allocation (TA) algorithm, used to assign the nominal control effort $\overline{u}$ computed by the MPC among the available actuators and providing the real thrust effort $\overline{u}_r$; a Wave Filter (WF) (Fossen and Strand, 1999) that allows to estimate the ship position $\overline{y}_r$ in the presence of external environment noise d affecting the measured output $\overline{y}_m$; the controller (MPC) has been tuned with respect to the LPV model of Eq. (5),

Table 1
Cybership II dynamical model parameters.

Parameter	Symbol	Value	Unit
Mass	m	23.8	kg
CG position	x_g	0.0425	m
Inertia moment	I_z	1.76	Nm
Added mass derivate	$X_{\dot{u}}$	− 2.0	kg
Added mass derivate	$Y_{\dot{v}}$	− 100	kg
Added mass derivate	$Y_{\dot{r}}$	0.0	kgm
Added mass derivate	$N_{\dot{r}}$	− 1.0	Kgm^2
Damping force coef.	X_u	− 2.0	kg/s
Damping force coef.	Y_v	− 7.0	kg/s
Damping moment coef.	N_r	− 0.5	Kgm^2/s