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Optimal direct adaptive soft switching multi-model predictive control using the gap metric for spacecraft attitude control in a wide range of operating points

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A B S T R A C T

In this paper, a new Multi-Input Multi-Output (MIMO) Multi-model Predictive Control (MMPC) with direct adaptive structure is used for spacecraft attitude control in a wide range of operating points and maneuvers. Because of the highly nonlinear dynamics, the linearized model characteristics are extremely depended to the operating points. In such cases, an expected performance, in the wide range of the operating points, never can be achieved using a single controller and single model (even instability may be anticipated). To handle this problem, in this paper, we divide the whole operating range of the spacecraft to construct sub-models (model bank) using a mathematical tool called as gap metric. Next, an adaptive MPC based on sub-models is designed. In this procedure, there are two problems: stability when switching among models and the minimum number of sub-models. Hard switching among models to update the controller's model causes extreme chattering on the control signal and reference tracking. The motivation of this paper is to present a new solution for the mentioned problems. To solve the first problem (remove chattering), an adaptive soft switching law to tune the controller parameters, when selecting new model, based on the Lyapunov theory is introduced as the main novelty of this paper. This guarantees the stability of the closed loop control system. For solution of the second problem, the number of optimal sub-models is obtained using different simulations. Finally, the effectiveness of the suggested method is proven via simulations.

1. Introduction

In highly nonlinear dynamic systems, getting an acceptable tracking performance in a wide range of the operating points is not feasible using a single controller based on linearization around an equilibrium point [1]. To make solvable, a criterion to analysis the model variations and uncertainties is essential. Using this criterion, consideration of a valid area for a single controller can be possible. Nonlinearity measure criteria are well-known tools to describe the amount of the nonlinearity in nonlinear dynamic systems [2]. The significance of the problem has caused numerous researches for two decades [3,7]. In the literature, different definitions for description of the nonlinearity have been presented. Most of them describe the distance of the nonlinear dynamics from the best linearized approximation [8,10].

The control of the lower nonlinear dynamics is possible using classical and simple controllers. On the other hand, highly nonlinear ones need advanced controllers. Multi-model predictive control (MMPC) is a feasible solution for tracking problem in highly nonlinear dynamics in the wide range of the operating points [1]. In [11], a bank of linear models (sub-models) is utilized to approximate the nonlinear dynamic system and handle the nonlinearity. The significant benefits of this control strategy are simple development of the sub-models, application in wide maneuvers and the robustness of the closed-loop control system. Literature [12] handles model mismatches using multi-models for H-infinity controller. The weak point of the mentioned reference is that there is no argument on how they select the operating points. In [13], a MMPC based on online estimation of the model is suggested. In this reference, the linear model is approximated using plant input–output data in online mode. The MMPC based on the fuzzy weights is the matter of [14] to construct a suitable global linear model with fuzzy weights. Simple structure and time-consuming are the main features of [14]. In [15], a weighted MMPC (WMMPC) with lock-up table weights is designed to control Continuous Stirred Tank Reactor (CSTR). Then, the main control signal applied to the CSTR is the weighted summation of local controllers. Indeed, in the cases that the number of models and controllers are small, the ap-

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plication of this control method is possible due to the limitation on real time implementation. Although the reviewed literature claims on excellent performance which is inevitable, in all of them, there is no stability analysis on the closed-loop control system that is an unavoidable part of the control theory, especially for switching controllers which has common problem of chattering. The mentioned gap motivates this paper to survey the MMPC problem in the stability point of view. In this view, the motivation of the control of highly nonlinear dynamic systems which are instable with single MPC makes [16] to introduce a new soft switching MMPC (SS-MMPC). In this literature, the parameters of MMPC are tuned to avoid instability from switching between only two sub-models. Moreover, expanding the proposed strategy in [16] to cover the whole range of the operating points is an open area for research that is the aim of this paper.

On the other hand, the distance among sub-models and operating points to extract linear models are the subject of literature [17] and [18]. To do this, gap metric is a well-known nonlinearity measure tool to determine how many sub-models should be considered in the model bank construction [19,20]. The gap tools, in fact, determine the amount of changes in the frequency response of two linear models extracted from a nonlinear dynamic system under operating point variations. More details about the gap are given [21]. To determine the distance of the sub-models, usually a threshold for the gap is considered. As an excellent application of this criterion, in [17], the authors used different nonlinearity criterion to partition the whole area of the pH neutralization process which in a well-known highly nonlinear dynamic system among control systems. Also, a sample work as [17] is done in [1] for hypersonic vehicle system due to the considerable nonlinearity.

The large number of the sub-models will improve the tracking performance exponentially. On the other hand, a few sub-models cause losing tracking performance (even may cause instability in some cases). Thus, a discussion for the selection of the number of the sub-models appears in design of MMPC. Up to now, many researches, to find the answer of this question, has been done, but there is no clear answer for this problem [22–24]. In [25], a strategy for optimal model bank generation is presented which is a modification for [23]. The authors in [17] claims that they have introduced a new metric definition to deduce the number of sub-models and keep the performance of the control system simultaneously.

Consideration of the above gaps through MMPC, to control highly nonlinear dynamic systems, is the motivation of this paper when focusing on spacecraft attitude control. In the attitude control, in addition to the robustness against model uncertainty, the anticipation of the control system accuracy with suitable settling time is inevitable [26]. In literature, different control methods as sliding mode [27] to improve the robustness, adaptive control [28] to encounter with uncertainty and intelligence controller [29] to learn and control the uncertain model have been proposed. Recently, due to the improvements of processors and ability of handling constraints, MPC has been applied to the attitude control problem [30]. The applications of MPC in the attitude control are the ability to handle different constraint such as quaternion constraint [31], keeping two spacecrafts in a special attitude for rendezvous mission [32] and also in the formation flying approach which a group of spacecrafts are controlled to have a pre-defined attitude [33].

In this paper, an adaptive soft switching MMPC (AMMPC) with direct structure is presented to control spacecraft nonlinear dynamics. In [1] (the main reference of this work), [17] and [18], there is no analysis about the stability of the closed-loop control system in the wide range of the operating points. Also, the optimal number of the sub-model is not given in [1]. To solve the mentioned gaps of [1,17] and [18], in this paper, we present the stability condition in the wide range of the operating points and the optimal sub-model numbers which together brings novelty.

The structure of this paper is as follows: in section 2, the spacecraft nonlinear dynamics is presented. Section 3 presents the concepts of the gap metric. In this section, the gap metric is selected as a suitable tool to compare the amount of the nonlinearity for model bank construction. In section 4, the design procedure of the controller including model bank construction and the stability analysis is presented and then, the next section presents simulation results. Finally, section 6 gives the conclusions.

2. Spacecraft nonlinear dynamics

This section gives briefly a description of the mathematical model of the spacecraft nonlinear dynamic. Using Euler equations, spacecraft dynamic equations in the body coordinate frame is

$$M = \frac{dH}{dt} + \omega \times H \tag{1}$$

where $\omega = [\omega_x\ \omega_y\ \omega_z]$ is the angular velocity in the body coordinate frame, H is the angular momentum and $M = [M_x\ M_y\ M_z]^T$ is generated torque using control moment gyros (CMGs). In this paper, we assume that applied torque is generated using CMGs. Also, with $H = I\omega$, Eq. (1) can be written as:

$$\dot{\omega} = \begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} = I^{-1}M - \left(I^{-1}\omega\right) \times (I\omega) \tag{2}$$

here, I is the inertia matrix of the rigid body as:

$$I = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} \tag{3}$$

Angular velocity in the inertial coordinate frame is written using transformation matrix between body and inertia coordinate frames:

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \frac{\sin\varphi \sin\theta}{\cos\theta} & \frac{\cos\varphi \sin\theta}{\cos\theta} \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \frac{\sin\varphi}{\cos\theta} & \frac{\cos\varphi}{\cos\theta} \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{4}$$

Eqs. (2) and (4) give the spacecraft nonlinear state space model. In this model, $X = [\omega_x\ \omega_y\ \omega_z\ \varphi\ \theta\ \psi]$ is the state space vector and $Y = [\varphi\ \theta\ \psi]$ is the output vector to control.

3. The criteria for description of the model behavior

Metrics are attractive tools to compare the behavior of a nonlinear dynamic system in different operating points. In fact, the answer of "how much does variation of the operating point influence on the linear model reliability?" can be found using metrics. As we mentioned former, there are varieties in the definition of the metrics. In this paper, the gap metric is selected to compare the nonlinear model behavior in the wide range of the operating points.

3.1. The gap metric

The gap metric was firstly introduced in [21]. It was firstly used to survey uncertainty in feedback control theory. The gap metric is defined as:

Definition. There is a gap between two linear system K_1 and K_2 equal to

$$\delta(K_1, K_2) = \|\Pi_{K_1} - \Pi_{K_2}\| \tag{5}$$

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