Self-tuning PID controller to three-axis stabilization of a satellite with unknown parameters

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Abstract

This paper addresses the three-axis stabilization of a satellite system in the presence of the gravity gradient and orbital eccentricity. Multivariable non-linear dynamics of the satellite system are converted into three well-known non-linear canonical independent models with unknown parameters. The new model is efficient and practical for designers to implement and analyze different control methodologies on satellite systems. A self-tuning PID controller is designed on the basis of the new proposed model to produce control signals for three reaction wheels in three axes. An adaptive algorithm is applied to tune and update gains of the PID controller and stability of the closed-loop system is guaranteed by using Lyapunov approach. Numerical simulations are performed to demonstrate feasibility and effectiveness of the self-tuning PID controller and a comparison with a fixed gain PID controller and a variable-structure controller is made.

1. Introduction

The attitude control of a satellite is an important part of most missions in the space. Not only a suitable control methodology, but also appropriate actuators should be applied in order to help achieve the goal of the mission and satisfy the constraints, e.g., solar radiation [1,2], reaction wheels [3–6], magnetic torque rod [7–9], thrusters [10], control moment gyro [11], etc. To stabilize the system with uncertainties, different methods have been proposed over the years. For instance, the adaptive method [12,13], H control theory [14,15], fuzzy control [16,17], optimal control [18], and feedback linearization [19], etc.

It is a well-known fact that PID controllers have dominated industrial control applications even in aerospace engineering [1], although there has been considerable interest to research about the implementation of advanced controllers. They are straightforward to use, as almost everyone with some basic knowledge in control engineering may be able to employ it satisfactorily.

The fixed gain PID controller cannot perfectly stabilize non-linear systems with uncertainties in terms of the model and parameters. To enhance the performance of the PID controller, different algorithms were proposed. As explained in Ref. [20] Newton–Raphson method was employed to adjust the gains of PID. A fuzzy-based self-tuning method was proposed in [21].

Additionally, some tuning algorithms based on the adaptive and robust methods were proposed in [22–26].

This paper presents the adaptive-based PID controller and develops it for the satellite system. First, some manipulations are applied in order that the system equations are in a form suitable for the design and analysis of the controller. These manipulations allow engineers to design a controller without having much information about parameters of the system. In order to fulfill this purpose, the multivariable non-linear dynamic of the satellite was converted into three prevalent non-linear canonical systems. One more advantage can be counted for the new model. In fact, this model can be considered as three independent systems where a different control system is applied in each axis.

Therefore, a non-linear PID based controller is designed for a satellite system. The controller has been designed for a satellite system as PIDs are being extensively used in many industries. In the literature, added to the self-tuning PID controller, there have been various controllers [27,28] designed for non-linear canonical systems those with unknown parameters. Among them, few have been employed and analyzed for satellite systems. The adaptive PID controller is stable against the parameter variations while a fixed-gain PID controller, designed according to the linear dynamic of the system, is vulnerable in the disturbances and uncertainties [10]. Furthermore, a non-linear controller, the one proposed for three reaction wheels based on a variable-structure controller, produces chattering effects [6].

To develop an adaptive self-tuning PID controller, the new canonical model is considered as the basic model. Then, the controller is designed and the stability of the closed-loop system...
is confirmed. In addition, some simulations are carried out. The results show that the new proposed method can stabilize the original non-linear system of the satellite in the presence of uncertainties and disturbances. The rest of the paper is organized as follows. In Section 2 the satellite system is attended and the uncertainties and disturbances. The rest of the paper is organized.

### Table 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$S_0$</td>
<td>Mass center of satellite</td>
</tr>
<tr>
<td>$X_0Y_0Z_0$</td>
<td>Body coordinate system</td>
</tr>
<tr>
<td>$X_0Y_0Z_0$</td>
<td>Orbital reference frame</td>
</tr>
<tr>
<td>$I_0$</td>
<td>Inertia matrix</td>
</tr>
<tr>
<td>$\omega_i$</td>
<td>Angular velocity vector</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>Angular velocity in i-axis, $i = X, Y, Z$</td>
</tr>
<tr>
<td>$\varphi, x, \psi$</td>
<td>Euler’s angles in $\varphi$, $x$, $\psi$, respectively</td>
</tr>
<tr>
<td>$c(\cdot), s(\cdot)$</td>
<td>cos ( ), sin ( ), respectively</td>
</tr>
<tr>
<td>$x$</td>
<td>State variable</td>
</tr>
<tr>
<td>$h_i$</td>
<td>Adjustable produced torque by reaction wheel in i-axis, $i = X, Y, Z$</td>
</tr>
<tr>
<td>$y_i$</td>
<td>Desired trajectory</td>
</tr>
<tr>
<td>$u_{wd}$</td>
<td>Produced control signal by self-tuning PID controller</td>
</tr>
<tr>
<td>$u^*$</td>
<td>Ideal control parameters vector</td>
</tr>
<tr>
<td>$R$</td>
<td>Orbital radius (circular orbit), semi-major axis (eccentric orbit)</td>
</tr>
</tbody>
</table>

The relation between the body angular velocities vector and the derivative of Euler’s angles is written as addressed in [10]

$$F = \ddot{\varphi} = \dot{\varphi} \dot{\psi} \omega_z - \dot{\psi} \omega_y$$

Then, Eq.(2) is rewritten as follows:

$$\dot{\varphi} = F - C \dot{\varphi}$$

where $F$ and $G$ are $3 \times 1$ and $3 \times 3$ matrices, respectively. The matrices $D$ and $I^{-1}$ can be written in the form of the diagonal and non-diagonal matrices

$$I^{-1} = I_{sd}^{-1} + I_{nd}^{-1}$$

where $D_1$ and $I_{sd}^{-1}$ are diagonal matrices and $D_2$ and $I_{nd}^{-1}$ are non-diagonal ones. From (6) we have

$$G = D_1 I_{sd}^{-1} + D_2 I_{nd}^{-1} + I_{nd}^{-1}$$

where $T_a$ is the interaction of axes. It causes the control action in an axis producing unwanted effect on the other axes. Forasmuch as the non-diagonal elements of the $I_2$ and $D$ are smaller than

### 2. Satellite model

The notations adopted throughout the paper are listed in Table 1. Moreover, the satellite system is shown in Fig. 1. $X_0Y_0Z_0$ is the orbital reference frame, $Z_0$ axis points toward the mass center of the Earth, $X_0$ is in the direction of the satellite velocity, and $Y_0$ represents the third axis of this right-handed taken frame. $(\varphi, x, \psi)$ are Euler’s angles made via rotating about $Z_0Y_0X_0$, respectively. Euler’s equation of motion can be written as

$$H + \omega_z H = T_g + T_d$$

$$H = I_0 \omega_0 + h_0 \dot{h}_0 = [h_0, h_1, h_2]^T$$

Fig. 1. System model, orbital and body reference frames.
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