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Optimization of fault-tolerant thruster configurations for satellite control

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Abstract

The fault tolerance of spacecraft actuators significantly affects the reliability of satellites and the likelihood of successful missions. To enhance the fault tolerance of the actuators, this study derives optimal fault-tolerant configurations of fixed thrusters that maximize the controllability of a fully-actuated or underactuated satellite. The proposed method optimizes thrust and torque directions generated by the thrusters. Thus a cost function in terms of the thruster locations and directions is defined as the summation of the generated control forces and torques with respect to the body-fixed frame. The optimal configuration is obtained by the successive use of an energy potential method that is motivated by Thomson's problem. Some numerical examples are provided that show the effectiveness of the proposed formulation and optimization method.

Keywords: Optimization; Fault tolerance; Thrusters

1. Introduction

The fault tolerance of spacecraft actuators significantly affects satellite reliability and the chances of mission success. One way of enhancing the fault tolerance against actuator failures is to use underactuated control, which enables the driving of satellites into desired states with lower number of inputs than the number of state variables. Underactuated control of satellites has been intensively studied, and many control techniques have been proposed (Krishnan et al., 1994; Tsiotras et al., 1995; Morin and Samson, 1997; Yoshimura and Hokamoto, 2011; Horri et al., 2012).

In practical situations, however, one of the difficulties in applying underactuated controllers is that input directions are restricted when some actuators fail. When actuators malfunction, the remaining actuators are not necessarily able to generate control torques and/or translational forces in the ideal directions, such as along the principal axes of inertia. Such restriction on the possible input directions makes underactuated controllers somewhat impractical. In other words, underactuated control can enhance the fault tolerance of a satellite as long as the controllability of the satellite is still sufficient even after some actuators have failed. In this context, this study derives the optimal fault-tolerant configurations of fixed thrusters that maximize the controllability of underactuated satellites.

A thruster generates a translational force and coupled torque in a single direction due to thruster mechanisms. Although the position and attitude of a satellite can be simultaneously controlled with thrusters, the unilateral control inputs complicate the proof of the controllability of the system. In fact, controllability theorems in the case of restricted input directions have not yet been proposed. The derivation of the controllability conditions is outside of the scope of this study. Instead, two controllability con-

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ditions used in Pena et al. (2000);Matsuno et al. (2014) are applied.

It is known that four thrusters are necessary for the attitude control of a fully-actuated satellite as shown in Yoshimura and Hokamoto (2011) and Sidi (1997). Underactuated controllers, however, enable attitude control with only three thrusters (Matsuno et al., 2014). Although several previous studies have discussed the minimum necessary number of thrusters and their configuration, few studies have considered underactuated control. Pena et al. (2000) showed an optimal and robust 6-thruster configuration that is robust against the failure of a single thruster. Jin et al. (1995) also provided an optimal thruster configuration that maximizes the margin of safety of the thrusters, with the thruster configuration being designed to attenuate external disturbances sufficiently. For gimbal thrusters, thruster configurations that consume less fuel are studied by Saberi and Mehdi (2015). These previous studies focus on disturbance rejection and fuel consumption, and the controllability associated with underactuated control systems is not considered.

The optimization of fixed-thruster configurations requires finding optimal thruster locations and directions with respect to a satellite body-fixed frame. We consider general thruster locations and directions, i.e., the thrusters generate translational forces and their coupled torques. A cost function for the controllability is built on the condition that translational forces and rotational torques must be able to be generated in any directions. This condition defines the cost function as the sum of the generated control forces and torques with respect to the body-fixed frame. The optimal thruster configuration can be derived using a solution to Thomson's problem, as applied in Yoshimura (2015). In the optimization method, by considering the geometric locations and directions of the thrusters as point charges, an arbitrary number of thrusters can be configured at equal distances, maximizing the available control forces and torques in all directions. That is, the controllability of the position and attitude of the satellite after actuator failures is maximized. Furthermore, applying different weights to the point charges can account for underactuated controllability. Some numerical examples are provided to demonstrate the effectiveness of the proposed formulation and the optimization method.

There a few papers that deal with translational and rotational motion control of an underactuated satellite. Yoshimura et al. (2016) showed an open-loop controller that can drive a satellite to arbitrary position and attitude with only four thrusters. Although this method is based on open loop controller, the analytical solution of the translational and rotational motion provides clues for trajectory design of the underactuated satellite. Pong (2010) also presented the translational and rotational motion control of an underactuated satellite. In this thesis, common control techniques such as model predictive control are studied for implementing the control of the underactuated satellite.

The rest of this paper is organized as follows. Section 2 formulates optimal thruster configurations in terms of the controllability of satellite position and attitude. The cost function to be minimized is interpreted as the summation of the inner products of translational forces and control torques. Section 3 demonstrates the optimization of the thruster configurations using a method based on the energy potential method. Section 4 gives some numerical examples of the optimal thruster configurations. Some conclusions are presented in Section 5.

2. Problem formulation

2.1. Satellite and thruster model

Thrusters generate translational forces with coupled torques. This paper considers the controllability of a satellite position and attitude using thrusters. The satellite position is considered to be a free-floating state, and orbital motion is not considered. The equations of motion of a free-floating satellite can be expressed with an affine system as:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + G(\boldsymbol{x})\boldsymbol{u} \tag{1}$$

where

$$\boldsymbol{x} = \begin{bmatrix} x & y & z & \boldsymbol{q}^T & \dot{x} & \dot{y} & \dot{z} & \boldsymbol{\omega}^T \end{bmatrix}^T \tag{2}$$

$$\boldsymbol{f}(\boldsymbol{x}) = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ 0.5[\tilde{\omega}]\boldsymbol{q} \\ \boldsymbol{0}_{3\times 1} \\ -I^{-1}(\boldsymbol{\omega} \times I\boldsymbol{\omega}) \end{bmatrix} \tag{3}$$

$$G(\boldsymbol{x}) = \begin{bmatrix} \boldsymbol{0}_{3\times 3} & \boldsymbol{0}_{3\times 3} \\ \boldsymbol{0}_{4\times 3} & \boldsymbol{0}_{4\times 3} \\ \frac{1}{m}R_{b/i}^T & \boldsymbol{0}_{3\times 3} \\ \boldsymbol{0}_{3\times 3} & I^{-1} \end{bmatrix} \tag{4}$$

$$\boldsymbol{u} = \begin{bmatrix} \boldsymbol{F}_b^T & \boldsymbol{T}_b^T \end{bmatrix}^T \tag{5}$$

The satellite position with respect to an inertial frame is expressed in terms of x, y and z. The attitude angle is formulated with a quaternion $\boldsymbol{q} = \begin{bmatrix} q_1 & q_2 & q_3 & q_4 \end{bmatrix}^T$, in which q_4 is the scalar part and the other variables form the vector component. The angular velocity is $\boldsymbol{\omega} = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T$. The satellite mass is m and the matrix I represents the moment of inertia of the satellite. The matrix $R_{b/i}$ is a directional cosine matrix from the inertial frame to the body-fixed frame. In Eq. (3), $[\tilde{\omega}]$ is defined for kinematics with quaternions as follows.

$$[\tilde{\omega}] = \begin{bmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{bmatrix} \tag{6}$$