Optimal Fault-Tolerant Configurations of Thrusters

Yasuhiro Yoshimura[1*] and Hirohisa Kojima[1]
[1]*Tokyo Metropolitan University, Japan*
yyoshi@tmu.ac.jp

Keyword : Fault Tolerant Systems, Thrusters, Underactuated Systems

Fault tolerance of spacecraft actuators significantly affects spacecraft reliability for mission success. One possible solution to enhance the fault tolerance against actuator failures is the use of underactuated control. Underactuated control enables controlling a satellite state to a desired state with less number of inputs than the number of state variables. Thus underactuated control for satellites has been intensively studied and many control techniques also have been proposed.
However, one of the difficulties to use underactuated control is restricted input directions when some actuators have failed. In practical situation of actuator malfunctions, the remained actuators are not necessarily able to generate control torques and/or translational forces along ideal directions such as the directions along the principal axes of inertia. Such restriction on the input directions makes it harder for the underactuated control to be applicable. In other words, underactuated control can enhance the fault tolerance of the satellite when the controllability considering the underactuated satellite is satisfied even after some actuators have failed. In this context, this study derives optimal fault-tolerant configurations of thrusters that maximize the controllability of the underactuated satellite.
One thruster generates translational forces and coupled torques in one direction due to the thruster mechanism. Although satellite position and attitude can be simultaneously controlled with thrusters, the restricted input direction complicates the proof the controllability of the system, because controllability theorems with unidirectional inputs have not been proposed. This study thus assumes the following two controllability conditions:

1) The system is controllable when translational forces and rotational torques can be generated in all directions.
2) The system is controllable when the thruster configuration satisfies the geometric condition proposed in [1].

The first condition is necessary and sufficient to control the position and attitude of a satellite. This condition, however, does not consider underactuated control explicitly. The second condition is derived for an underactuated satellite with only three thrusters. Although the necessity for the position and attitude control is not proved, satisfying this condition is sufficient for controlling the position and attitude of the satellite.
This study expresses a thruster configuration, i.e., thruster position and attitude with respect to a body-fixed frame, using dual-quaternions. The dual-quaternion expression simplifies rotational torques and translational forces generated by the thrusters. Then a cost function in terms of the dual-quaternions is defined as the sum of the generated control forces and torques with respect to the body-fixed frame. The optimal thruster configuration is derived using a solution to Thomson's problem as used in [2]. In the optimization method, considering the geometric position and attitude of the thrusters as point charges, the arbitrary number of thrusters can be configured in an equal distance, which maximizes available control forces and torques in all directions. That is, the controllability of the position and attitude of the satellite under a few actuator failures is also maximized. Some numerical simulations for different weightings show the effectiveness of the proposed optimization method.

References

[1] Matsuno, T., Yoshimura, Y., and Hokamoto, S., "Geometric conditions of thrusters for 3D attitude control of a free-floating rigid spacecraft," *Journal| MESA*, vol. 5, Feb. 2014, pp. 83–95.
[2] Yoshimura, Y., "Optimal Fault-Tolerant Configurations of Control Moment Gyros," *Journal of Guidance, Control, and Dynamics*, vol. 38, 2015, pp. 2460–2467.