DEVELOPMENT OF THRUST CONTROL SYSTEM FOR SPACECRAFT'S DOCKING MANEUVER

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Abstract

A system that automatically controls the movement of multiple spacecraft, considering their motion in space, can be applied in various ways in space planning. Specifically, effective docking technology between spacecraft is critical for executing orbital servicing missions. Therefore, the development of precise thrust control system is essential for the docking process in space. This paper proposes the design process for the thrust control system using reaction thrusters, followed by the simulation of the docking control system. A 4-DOF simulation, aimed at regulating yaw attitude and the x, y, and z positions, employed eight reaction thrusters. Subsequently, a second simulation utilized thirty-two reaction thrusters in 6-DOF control. The simulation results demonstrate that the proposed thrust control system can control the position and attitude of the spacecraft within a small error margin. The numerous simulations should be conducted using more robust thrust control system as a part of future work. This thrust control system could be applied to various space missions such as satellite repair, fuel replenishment and space debris removal.

Keywords: Docking, Spacecraft, Thrust control, Reaction thruster

1. Introduction

On-orbit servicing has been a critical issue in space exploration for several years [1]. The ability to repair and refuel satellites or spacecraft while in orbit is essential for various space missions, making the movement of multiple spacecraft an important problem in space planning. During on-orbit servicing missions, a relation between the target and chaser satellites should be considered. This relation can be achieved through docking or berthing. Docking involves the mechanical coupling of two spacecraft where the guidance-navigation-control (GNC) system of the chaser controls the relative state of the bodies to be mated. Berthing, on the other hand, occurs when the GNC system delivers the servicer vehicle to a meeting position, followed by the grappling of one satellite by a manipulator, which is placed on either the chaser or target, steering them to a common coupling port [2].

Over the decades, the docking mechanism has evolved significantly. This paper focuses on the thrust control system for spacecraft docking using reaction thrusters. Several considerations are essential in developing the thrust control system, with thruster modeling and allocation being among the most critical. For instance, Kim [3], in designing a thruster-based controller for the trajectory tracking of a ground test model of a lunar lander, proposed a thrust distribution method based on the thruster arrangement configuration and modeled the thrusters. Similarly, Mu [4] configured the reaction control system arrangement for a Reusable Launch Vehicle. Thruster allocation for space missions, particularly for docking, has also seen significant advancements over the decades. Notable developments include Boeing's X-37 [5], SpaceX's Dragon [6], and NASA's HL-20 [7]. These efforts have collectively contributed to the progress in thruster allocation strategies and control systems for space docking missions.

Another critical aspect is the docking control system. Singla [8] developed an adaptive output feedback control for spacecraft rendezvous and docking under measurement uncertainty. The spacecraft's inertia changes over time due to fuel consumption and changes in solar array orientation. These output errors can result from sensor calibration errors, systematic biases, or stochastic disturbances. The proposed control laws were evaluated for their performance in achieving stable and bounded tracking of the relative orbit and attitude trajectories, considering unmodeled external disturbances, parametric disturbances, and realistic position and attitude measurement errors. When the target is tumbling, the chaser must perform large attitude maneuvers. In such cases, nonlinear optimal control can be employed to address these challenges [9]. If there is misalignment in actuators during rendezvous, which can affect the final docking process such as translational motion, a time-varying sliding mode surface can be constructed. A control scheme with the sliding manifold is proposed to achieve the fixed-time convergence of relative parameter tracking errors [10].

This paper proposes a design process for the thrust control system. Chapter 2 addresses the design of the thrust control system in detail. The simulation results are presented in Chapter 3, and Chapter 4 concludes the paper.

2. Design of thrust control system

The design process of a thrust control system, consisting of three steps - on/off controller modeling, thruster modeling, and thruster allocation - is proposed. Figure 1 provides an overview of the thrust control system. The controller modeling involves the designing the controller and on/off modulator. The thruster is operated by using on/off controllers through an input signal. The controller is positioned before the on/off modulator and the output signal from the controller serving as the input signal for the on/off modulator. Next, the thruster modeling process is conducted. The thruster typically has ignition delay and nonlinear delay which affect the response time of the thruster before reaching the actual thrust value. It is crucial to incorporate this characteristic into the thruster model. Finally, the thrust and torque values should be considered according to the allocation of the thrusters which is referred as β. In order to perform stable docking, it is necessary to derive the derivation of the thrust and torque based on the arrangement of the main thruster, which controls altitude, and the reaction thruster, which controls attitude. By following these steps, a comprehensive thrust control system can be developed, ensuring effective and stable docking operations.

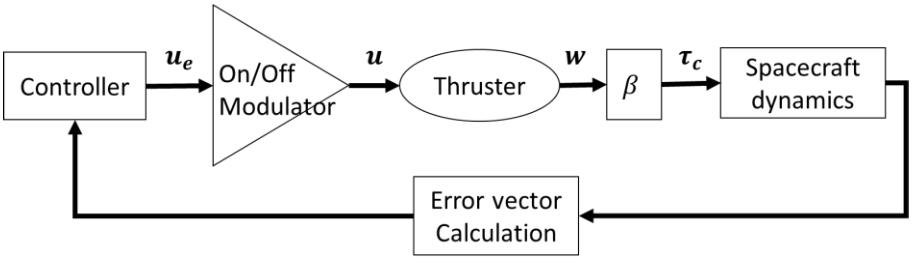

Figure 1 – Overview of the thrust control system.

2.1 On/off controller

To commence the study, the modeling of the on/off controller should be initiated. This controller comprises both a controller and an on/off modulator. Various thrust control methodologies for the controller have already been established, including PID (Proportional-Integral-Differential) control [11] and sliding mode control [12]. For the on/off modulator, PWM (Pulse-Width Modulation) and PWPFM (Pulse-Width Pulse-Frequency Modulation) controllers could be utilized to regulate the output signal [13]. The thruster maintains a constant value for its output rather than adjustable continuous output due to characteristics of thruster. The PWM circuit periodically generates on-off signals to modulate a continuous input signal into a pulse form, thereby approximating the average behavior of the input signal. Consequently, PWM is commonly employed in on/off controller systems to reduce the energy consumption of the actuator. This method involves comparing the control input signal with the carrier signal and adjusting the pulse width accordingly. PWPFM, on the other hand, distinguishes itself from PWM by incorporating feedback from a 1st order filter signal to introduce relative variability in the frequency of the output signal. Being Pseudo-Linear, PWPFM offers design flexibility using various parameters Additionally, it ensures low fuel consumption and high accuracy, particularly in the presence of vibration. However, at high frequencies, PWPFM introduces phase delays and exhibits non-linear characteristics, making challenges in determining precise stability margins.

2.2 Thrust modelling

Due to an ignition delay and a nonlinear delay of thruster, an accurate thrust modeling becomes imperative. One approach to capture these characteristics is through the utilization of a 1st order linear differential equation. This method offers a simplified depiction of the relationship between input and output, facilitating comprehension of the system's state, stability, and transfer function. Alternatively, employing a 2nd order differential equation provides a more comprehensive representation. By incorporating a 2nd order equation, greater attention can be paid to the ignition delay, resulting in a longer rise time compared to the 1st order system. Equation (1) represents 1st order system while Eq. (2) represents 2nd order system. u denotes the actual control input, v denotes the require input of thruster, and T denotes the time constant. To determine the performance of the system, both 1st and 2nd order system should be analyzed. Figure 2 illustrates the comparative behaviors of these systems, offering insights into their respective characteristics.

$$T\dot{u} + u = v \tag{1}$$

$$T_v T_u \ddot{u} + T_v \dot{u} + v = w \tag{2}$$

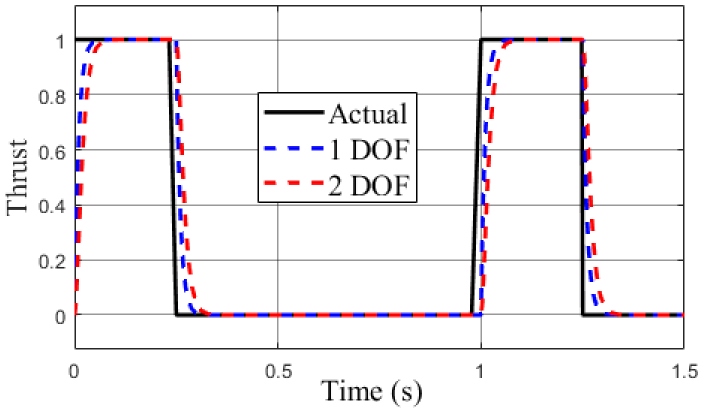

Figure 2 – Thrust modelling.

2.3 Thrust allocation

Various types of thrusters can serve as attitude control mechanisms, including reaction wheels, control moment gyroscopes, magnetic torquers, and reaction thrusters. This paper focuses on utilizing reaction thrusters to regulate the spacecraft's attitude during the docking phase. Reaction thrusters are used as an alternative to momentum exchange devices when disturbance torques exceed the control authority of momentum exchange devices [14]. The reaction thrusters could be allocated with the process shown in Fig. 3. The essential number of the reaction thrusters are calculated as Eq. (3) while J denotes the number of reaction thrusters, D denotes the number of dimensional tasks, and R denotes the level of redundancy [14~16].

$$J \geq D + 2R + 1 \tag{3}$$

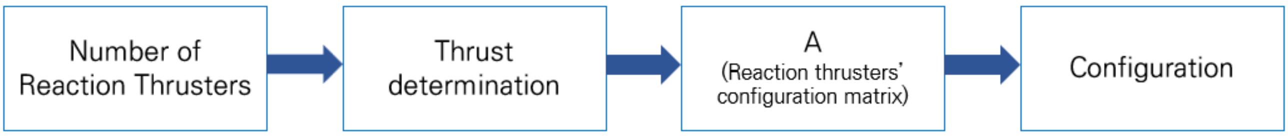

Figure 3 – Process of thruster allocation.

Previous studies have extensively investigated thruster allocation for spacecraft docking operations. As the objectives of this research, the spacecraft under consideration shares a resemblance to the small-sized X-37. Therefore, the thruster allocation scheme employed by the X-37 spacecraft serves as a valuable reference point. Moreover, with Space X's ongoing development of the Dragon, there arises the possibility of leveraging its potentially more fuel-efficient design in the thrust allocation process. For instance, the X-37 spacecraft features twelve primary attitude control thrusters and fourteen vernier attitude control thrusters, while the Dragon spacecraft is equipped with sixteen attitude control thrusters [5, 6]. Drawing upon the configurations of these spacecraft offers insights into optimal thruster allocation strategies for achieving docking maneuvers effectively.

3. Simulation

To prove the robustness of the proposed thrust control system, two simulations were conducted. First, 4-DOF (Degree of freedom) simulation using PD control was conducted and next, 6-DOF simulation using PD control was conducted. The first simulation represents the thrust control system of 3-DOF (position) and 1-DOF (yaw), while the second represents 6-DOF simulation. The simulations were conducted under several assumptions. Only translational motion and rotational motion of the rigid body were considered as shown in Eq. (4) and Eq. (5), while the consumption of the fuel, the sloshing, the reaction thrusters' mass and the moment of inertia were ignored.

$$\sum F = \frac{d}{dt}\vec{L} \quad = m\frac{d}{dt}\vec{v} \quad = m(\dot{\vec{v}} + \vec{\omega} \times \vec{v}) \tag{4}$$

$$\sum T = \frac{d}{dt}\vec{H} \quad = I\frac{d}{dt}\vec{\omega} \quad = I(\dot{\vec{\omega}} + \vec{\omega} \times \vec{\omega}) \tag{5}$$

3.1 4-DOF simulation

For the first simulation, the specification of the spacecraft is represented in Table 1 while the spacecraft is assumed as a cube.

Table 1. Specifications of spacecraft used in simulation

Size	4 x 4 x 8 m^3
Mass	364 kg
Moment of Inertia	$I = \begin{bmatrix} 2426 & 0 & 0 \\ 0 & 2426 & 0 \\ 0 & 0 & 970 \end{bmatrix} kgm^2$

The first simulation was conducted using eight reaction thrusters, as shown in Fig. 4. According to Eq. 3, a minimum of five reaction thrusters is essential. An overview of the thrust control system is depicted in Fig. 5. The attitude control, utilizing PD control and PWM, is executed with a first-order thruster system comprising eight reaction thrusters.

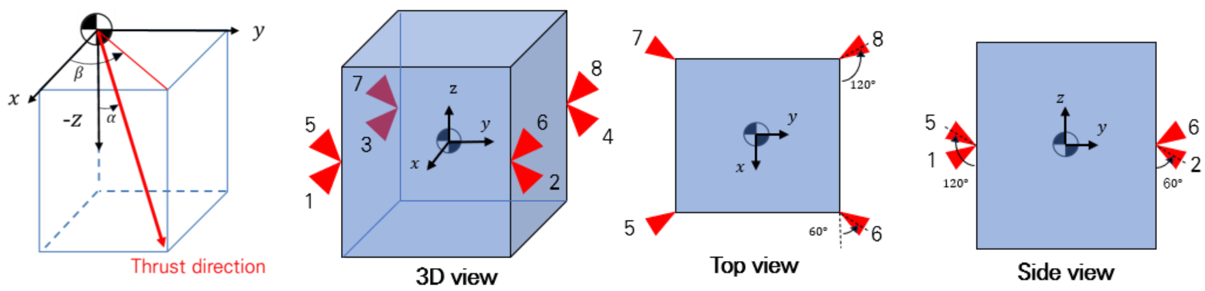

Figure 4 – Allocation of eight reaction thrusters.

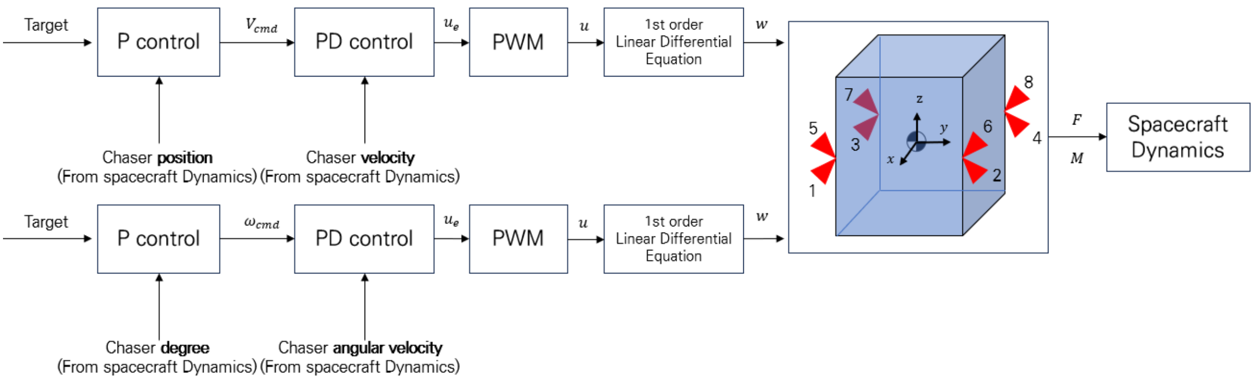

Figure 5 – Overview of the first simulation.

Figure 6 depicts the result of the simulation. The simulations were conducted with four cases due to the 4-DOF. The simulations considering the attitude control of yaw, and the position control of x, y, z were conducted progressively. The result of case 1 ~ case 4 shows that the proposed thrust control system could control the spacecraft respectively.

	Time sec	Aim of Target
Case 1	0 ~ 250	(0, 0, 0, 10)
Case 2	250 ~ 500	(4, 0, 0, 10)
Case 3	500 ~ 670	(4, -2, 0, 10)
Case 4	670 ~ 800	(4, -2, 3, 10)

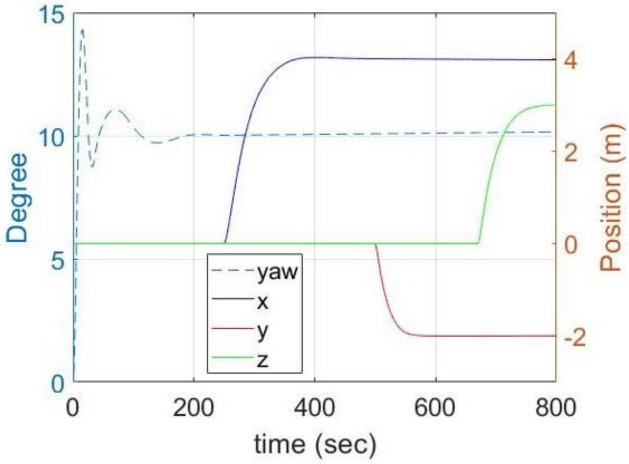

Figure 6 – Result of the first simulation.

3.2 6-DOF simulation

Next, the simulation was also conducted using PD control and PWM. For this simulation, thirty-two reaction thrusters were allocated. Additionally, the direction of thrust injection was altered as shown in Fig. 7 and Eq. 6. Due to the change in thrust injection direction, the moment of inertia also changed as per Eq. 7. The thrust injection vector is depicted in Eq. 6. The configuration of sixteen reaction thrusters is one of the designed allocations represented in [14]. As shown in Fig. 7, the thirty-two reaction thrusters are arranged in pairs, with two thrusters placed at each of the positions where the sixteen reaction thrusters were originally located. Among the thirty-two reaction thrusters, sixteen are responsible for controlling the position, while the other sixteen control the attitude of the spacecraft.

$$F_i = \begin{bmatrix} F_{x_i} \\ F_{y_i} \\ F_{z_i} \end{bmatrix} = -F \begin{bmatrix} -\cos(\alpha_i) \\ \sin(\alpha_i)\cos(\beta_i) \\ \sin(\alpha_i)\sin(\beta_i) \end{bmatrix} \tag{6}$$

$$I = \begin{bmatrix} 2541 & 0 & 0 \\ 0 & 6353 & 0 \\ 0 & 0 & 6353 \end{bmatrix} kgm^2 \tag{7}$$

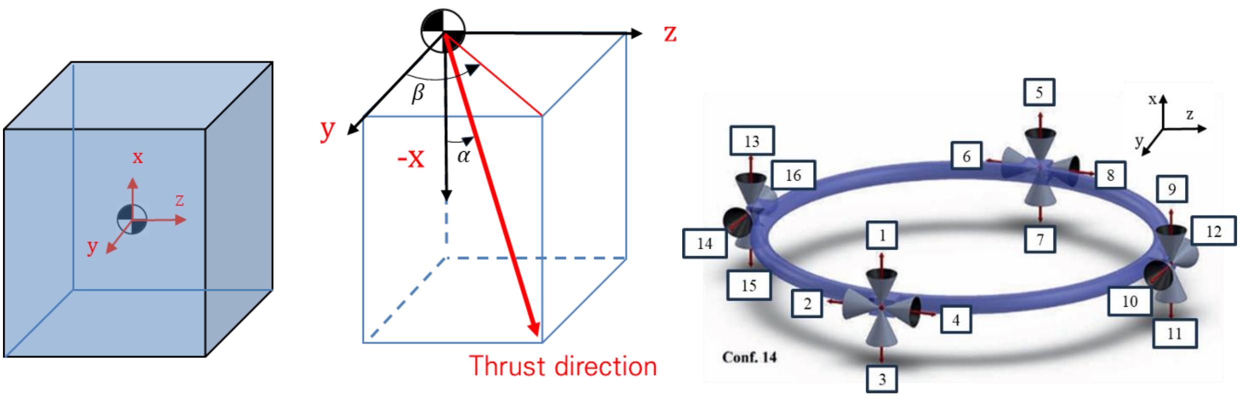

Figure 7 – Allocation of sixteen reaction thrusters.

The simulation results are presented in Table 2. Table 2 shows the calculated errors for position, velocity, angle, and angular velocity. To validate the thrust control system, the simulation errors are compared to the error thresholds established as standards in [17] and [18]. The simulation results, using both Euler and Quaternion methods, exhibit errors lower than these standards.

Table 2. Result of the second simulation

Error		Limitation value		Simulation result	
		Standard 1	Standard 2	Euler	Quaternion
Position	Lateral Y	-	0.013 m	0.013 m	0.008 m
	Lateral Z	-	0.05 m	0.008 m	0.008 m
Velocity	Longitudinal X	0.05~0.1 m/sec	0.02~0.04 m/sec	0.0005 m/sec	0.0005 m/sec
	Lateral Y	Vector sum 0.04 m/sec	0.01 m/sec	0.0007 m/sec	0.0007 m/sec
	Lateral Z		0.01 m/sec	0.0005 m/sec	0.0004 m/sec
Angle	Roll	4 deg	3 deg	0.06 deg	0.14 deg
	Pitch	Vector sum 4 deg	3 deg	0.16 deg	0.16 deg
	Yaw		3 deg	0.1 deg	0.1 deg
Angular velocity	Roll rate	0.2 deg/sec	0.1 deg/s	0.005 deg/sec	0.02 deg/sec
	Pitch rate	Vector sum 0.2 deg/sec	0.1 deg/s	0.017 deg/sec	0.012 deg/sec
	Yaw rate		0.1 deg/s	0.01 deg/sec	0.008 deg/sec

4. Conclusion

In this paper, a design procedure for a thrust control system using reaction thrusters is proposed. The thrust control system comprises an on/off controller, thrust modeling, and thrust allocation. The on/off controller combines a conventional controller, such as PID or sliding mode control, with an on/off modulator like PWM or PWPFM. To simulate ignition delay and nonlinear delay of the thruster, the thrust is modeled using first and second-order linear differential equations. The number and allocation of the reaction thrusters are also considered.

To validate the robustness of the proposed thrust control system, two simulations were conducted. The first simulation, a 4-DOF simulation, aimed to control the yaw attitude and the x, y, and z positions. In this simulation, eight reaction thrusters were allocated as shown in Fig. 4. The second simulation involved thirty-two reaction thrusters allocated based on a previous study. Both simulations demonstrated that the proposed thrust control system could control the position and attitude of the spacecraft within a small error margin.

As a future work, various scenarios based on different thruster allocations and control methods could be concerned. Moreover, the more precise attitude control method needs to be developed. Once a more robust thrust control system is developed, its performance should be compared across various scenarios to ensure reliability and effectiveness in real docking situations. The proposed thrust control system could be applied to various space missions.

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6. Copyright Statement

7. Acknowledgement

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