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Abort recovery strategy for future vertical landing systems

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ABSTRACT

This paper summarizes the abort recovery strategy for future vertical landing spacecraft in case of single engine failure, by applying state-of-art non-linear control law.

The abort recovery strategy applied to future vertical landing systems with multiple engines are composed of two approaches. First is to shutdown the counter engine of the failed engine in order to minimize the attitude perturbation. And the second, which is the key approach, is applying a nonlinear control law. Such an approach has the robustness to the large attitude motion, and also to the variation in weight, moment of inertia and center of gravity. The control law applied has been developed under the collaboration with Nagoya University. To demonstrate the above mentioned strategy, Mitsubishi Heavy Industries is preparing flight test by a subscale demonstrator called “OEEX”, which stands for “One Engine inoperative EXperimental vehicle”. The results of application of such strategy are described. Also, the status of the OEEX is presented.

1. Introduction

MHI is supporting JAXA in the research and development of Reusable Sounding Rocket, which is a suborbital vehicle with a capability to return to the launch site and land vertically (Fig. 1) [1]. We believe such a vehicle is the first major key stone to the paradigm changing reusable launch vehicle.

MHI is also one of major players in the international space exploration activities. We are one of the members of industrial partners which support international government agencies in studies of space exploration. The near term target of space exploration is to explore the lunar surface. MHI is studying lunar landing technologies to support JAXA for missions such as SELENE-2 (Fig. 2) [2], which is an unmanned lunar lander studied by JAXA.

There are many technical challenges to realize aforementioned systems. One of the key technologies is guidance and control of return flight and landing. Since both Reusable Sounding Rocket and lunar lander have severe mass constrains. However, it is also important to have sufficient vehicle or crew safety, and have abort recovery capability, even on single engine failure, which in turn would increase the vehicle mass. Therefore it is necessary to minimize the budget of propellant for landing.

As for Reusable Sounding Rocket, it is equipped with four engines. And in case of single engine failure, remaining engines are throttled-up and transition to abort flight to return safely.

However, during the transitional condition from the moment of engine failure to the throttle-up condition, a large unstable attitude motion occurs to the vehicle. Through the study of vehicle control, we realized that it is difficult to control the vehicle with classical optimal control approach.

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Fig. 1. Reusable Sounding Rocket.

Fig. 2. SELENE-2.

We therefore have begun to study of abort recovery strategy by applying a more robust control algorithm, and combine with the approach in shutting down the failed engine as well as the counter engine, to minimize the attitude motion.

We also have considered that we need to actually demonstrate such an algorithm with a small demonstrator to increase the readiness level of such approach. The sub-scale demonstrator thus being prepared is called the OEEX, which stands for "One Engine inoperative EXperimental vehicle".

MHI has begun such study since 2013. This paper describes status of these activities.

2. Guidance and Control Algorithm

2.1. Overview

In order to land at the specific point, such as launch site or lunar surface, following three parameters must be controlled.

- Altitude
- Horizontal position
- Attitude

In this chapter, algorithms for controlling above parameters are described. The robust control algorithm has been applied to the attitude control of the vehicle. However, since these parameters interact with each other, control algorithms for all three parameters are described. Furthermore, since our study has focused on applying that to our demonstrator OEEX, algorithms are described in terms of OEEX characteristics. Details of OEEX are described in chapter III.

Fig. 3 represents for the definition of vehicle coordinate system for OEEX guidance and control algorithm.

2.2. Altitude control

A servo system with PID feedback has been introduced for altitude control. When OEEX lifts off, or detects its altitude less than desired value, GCC (Guidance and Control Computer) sends signals to engines to throttle up. The altitude control is described as follows

$$F_{in} = -K_{P.H}\left(x_{ref} - x\right) - K_{D,H}\dot{x} - K_{I.H}\int \left(x_{ref} - x\right)dt \qquad (1)$$

where $F_{in}$is commanded total thrust value send from GCC, x_{ref} represents for desired altitude of OEEX, and $K_{P.H}, K_{D.H}, K_{I.H}$ represent for PID feedback gains. The time profile of x_{ref} is pre-determined in off-line process, which implicitly controls the vertical speed.

In OEEX, engine thrust responses are not adequate for attitude control. Therefore, thrust control is used solely for attitude control, and all engines receive same thrust command.

2.3. Horizontal position control

OEEX is equipped with four engines as power sources. Therefore, the only way to move horizontally is to incline the attitude of OEEX itself. As a consequence, horizontal control function creates the reference of the attitude as follows;

$$\theta_{ref} = -K_{P.Z}\left(z_{ref} - z\right) - K_{D,Z}\dot{z} - K_{I.Z}\int \left(z_{ref} - z\right)dt$$
$$\psi_{ref} = -K_{P.Y}\left(y_{ref} - y\right) - K_{D,Y}\dot{y} - K_{I.Y}\int \left(y_{ref} - y\right)dt \qquad (2)$$

where θ_{ref}/ψ_{ref} are reference pitch/yaw attitude, and y_{ref}, z_{ref} represent the desired horizontal position of OEEX. $K_{P.Y}, K_{D.Y}, K_{I.Y}, K_{P.Z}, K_{D.Z}, K_{I.Z}$ are for PID feedback gains.

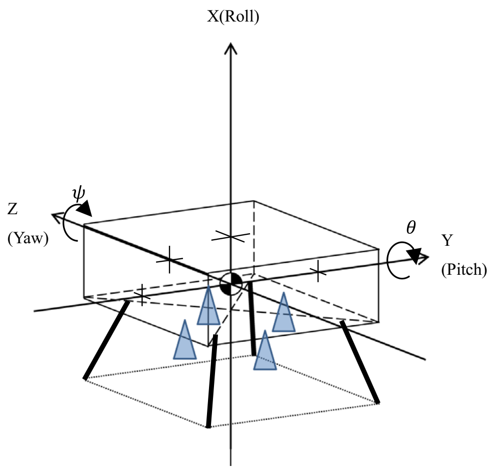

Fig. 3. Coordinate system for OEEX guidance and control algorithm.