Extending the Capability of Attitude Control Systems to Assist Satellite Docking Missions

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Abstract

Docking an in-orbit satellite by another satellite is a challenging task, especially when the target satellite is not co-operative or not originally designed for docking operation. This paper discusses docking operation and proposes an attitude control method capable of assisting docking operation. Simulation study has demonstrated that the method can promisingly assist soft docking and therefore reduces the requirements for docking interface design.

1. Introduction

Because of the long development cycles and high manufacturing costs, people have been dreaming to fix malfunctioning satellites or upgrade aging satellites in orbit. This desire has become more desperate then ever because the population of satellites in service has significantly increased in recent years. With the advances of modern technologies, it may soon become reality to provide services to the satellites in orbit. An essential and critical step for any on-orbit servicing mission is the docking and capture of the satellite to be serviced by the servicing spacecraft. Docking is a difficult and risky task because of various potential problems associated with it, such as misaligning with or jamming the target interface, crashing into, kicking away, or even tumbling the target satellite. In order to avoid these unfortunate problems, the docking vehicle's attitude control system is normally turned off prior to docking and a docking interface device is used to complete the docking operation. MD Robotics has been studying and developing prototypes of various docking interface devices in the past few years. Our study has found that a certain degree of assistance from the attitude control system of a docking spacecraft during the docking operation can significantly reduce difficulties that the docking interface device faces, and thus, reduces the sophistication/cost of the interface or increases the reliability of the docking operation. Such a finding has driven this research work.

2. Docking Operation

Satellite docking has been a relatively new area of study and practice in aerospace history. NASDA conducted a docking experiment in its technology demonstration mission ETS-7 in 1998-1999 and has claimed it was the first of the kind [2]. DAPPA initiated the development of a technology demonstration program involving satellite docking in late 2000 [3]. Currently, the most popular concept of docking operation would consists of: (1) performing rendezvous within close range at low manoeuvre speed; (2) shutting off the thrust engine after the docking interface are aligned within the docking envelop (the rendezvous is completed); (3) free-flying toward and contact the target satellite at its docking interface; (4) performing soft docking in which one side of the interface physically enters into the capture envelope of the other side; and (5) activating the capture mechanism to joint the two satellites and then rigidize the two satellites together. A drawback of such a docking procedure is that the soft docking is not actively controlled (soft docking is defined as the two satellites are in contact but have not been mechanically jointed together). Instead, it relies totally on the relative speed of the two satellites and the geometry of the mating interfaces. Our simulation study has shown that a passive soft-docking may not be completed for some common reasons such as friction too high, docking speed too low, compliance not enough (or stiffness too high), target inertia too small, initial misalignments too large, etc. What happens is that the two satellites start to either move together at the same speed or bounce away before they are fully mated and locked. If such a situation happens, the docking operation fails. A second trial of the procedure, if possible, would require tremendous time and fuel because the docking spacecraft will probably have to re-adjust its orbit and speed, and repeat all the steps from (1) through (5) again. However, there is a possible solution without repeating the entire operation if the said failure ever happens or about to happen. That is to turn on the thrust engine of the docking spacecraft and push it further with active attitude manoeuvre toward the target satellite. Such an additional thrust, if being controlled properly, will be able to ensure a smooth completion of the soft docking.

3. Attitude Control System

Attitude control systems (ACS), as its name clearly describes, are designed for controlling the attitude of spacecraft in space without any physical contact with another object in the orbit. ACS have typical characteristics of slow responding and small accelerating capabilities. The challenge here is how to make the ACS capable of assisting a docking operation, which has a strong dynamic behaviour in nature. Moreover, the technology currently available does not allow the use of proportional thruster valves in space, which thus prevents the use of the classical PID control laws. Therefore, spacecraft attitude and position are controlled by the use of on-off thruster valves, which introduces nonlinearities to the dynamic system. The usual scheme to control a spacecraft with on-off thrusters is based on the error phase plane, defined as that with spacecraft attitude error e and error-rate $\dot{e}$ as coordinates. The on-and-off switching is determined by switching lines in the phase plane and can become complex, as is the case in the phase plane controller of the Space Shuttle [4]. To simplify the switching logic, two switching lines with equations $e + \lambda\dot{e} = \pm\delta$ can be used. The deadband limits $[-\delta, \delta]$ are determined by attitude limit requirements, while the slope of the switching lines, by the desired rate of convergence towards equilibrium and by the rate limits. This switching logic can be represented as a relay with a deadband, where the input is $e + \lambda\dot{e}$, the left-hand side of the switching-line equations [5].

In this research work, it is planned to equip the docking satellite with a force moment sensor (FMS) at the docking interface. The attitude controller described above will be modified to use the FMS feedback information to control the thrusters in order to adjust the attitude of the docking spacecraft and provide a smooth and successful soft docking. For example this could be done by adding a term proportional to the error on the force read by the FMS, f_{FMS}, and the desired one, f_{des}, i.e., $e + \lambda\dot{e} + \beta e_f = \pm\delta$ where $e_f = f_{des} - f_{FMS}$. Moreover, due to the difficulty of manufacturing good FMS for space use, special attention will be given in the design of the controller such that it does not require sophisticated FMS, e.g., precision, bandwidth, range, etc.

4. Simulation Study

Due to the inherent nonlinearities of the spacecraft dynamics, the on-off thrusters controller, and the contact dynamics, it is nearly impossible to use analytical methods to develop the controller proposed in Section 3. Instead, simulation becomes essential in developing such a controller. MD Robotics, in collaboration with CSA, is developing a high-fidelity satellite docking simulator based on its validated contact dynamics technology and software [1]. The simulator can be conveniently used for concept evaluation and quick prototyping of docking interfaces design and docking missions study. An early version of the simulator has been used to study various designs of docking systems and different scenarios of docking operations. Numerous simulation results have suggested that, with the help of a capable ACS, many difficult docking operations can be confidently accomplished without changing design of the docking interface or tightening the operational requirements. The resulting contact behaviour of the soft-docking phase will also be much smoother. The research work of designing such an advanced ACS is still underway. Some detailed analysis results of the work will be presented at the conference.

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