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Postcapture stabilization of space robots considering actuator failures with bounded torques

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Abstract Space robotics is regarded as one of the most impressing approaches for space debris removal missions. Due to the residual momentum of debris, it is essential to stabilize the base rapidly after capture. This paper presents a novel control strategy for stabilization of a space robot in postcapture considering actuator failures and bounded torques. In the control strategy, the motion of the manipulator is not regarded as a disturbance to the base; in contrast, it is utilized to compensate for the limitation of the control torques by means of an inverse dynamical model of the system. Different scenarios where actuators are external mechanisms or momentum exchange devices have been carried out, and for actuator failures, both single- and two-actuator failures have been considered. Regarding to the performance of actuators, control torques are bounded. In cases that either single or two actuators have failed, the base can be stabilized kinematically when actuators are external mechanisms, but can only be stabilized dynamically when only momentum exchange devices are used. Finally, a space robot with a seven-degree-of-freedom manipulator in postcapture is studied to verify the validity and feasibility of the proposed control scheme. Simulation results show that the whole system can be stabilized rapidly.

1. Introduction

The earth's orbit is in a serious predicament caused by millions of space debris.[1] Fig. 1 shows the number of objects in the earth's orbit according to Ref. 2.

According to the Kessler syndrome, collisions among debris would increase the amount of debris even if all the launches into space would be stopped immediately.[3] To better preserve

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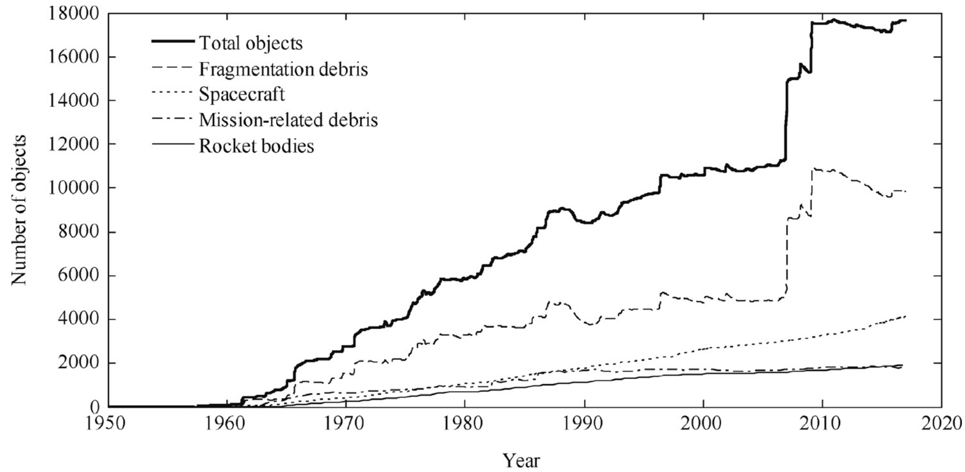

Fig. 1 Monthly number of objects in the earth's orbit by object type in Ref. 2 Credit: NASA.

the environment for future missions, active debris removal must be done.[4] The earth's orbit is a key environment to both private and military sectors, providing services that the modern world relies upon.[5] Space robotics is considered as one of the most promising approaches for orbital debris removal missions.[6] Some missions about space robots have been successfully launched like Orbital Express[7] and Engineering Test Satellite VII (ETS-VII).[8]

Most of the threatening space debris pieces are tumbling due to their residual angular momenta.[1] It is essential to stabilize the system in postcapture so as to meet the expected requirements of space missions such as communication. Many works have been done for stabilizing space robots in postcapture.[9–13] However, in the existing studies, it is assumed that the attitude control system (ACS) works well, and a control torque can be generated along three axes for control purposes, although from different actuators. A rapid control strategy for space robots in postcapture with actuator failures has not been considered before.

Actuator failure can cause serious problems for space missions, examples including GPS BII-07, Galaxy IV, and Hubble.[14] For the ACS of spacecrafts, there are mainly two different kinds of actuators: one can be regarded as some external mechanisms like gas jets, while for the other, the control torque can be regarded as an internal torque, which is generated by momentum exchange devices such as reaction and momentum wheels.

Researchers have done a lot of work about attitude control of underactuated satellites. It was firstly conducted by Crouch, who provided necessary and sufficient conditions for control of a satellite in cases that thrusters could yield one, two, or three independent torques, while for momentum exchange devices, controllability was shown to be impossible with fewer than three independent actuators.[15] Tsiotras et al. conducted a control law for stabilizing the attitude of a nonsymmetric rigid body spacecraft with only two pairs of gas jet actuators based on the theory of differentially flat systems.[16,17] Kim and Turner introduced three single-axis maneuvers for a satellite with a control torque only along two axes, in which the initial and final times are fixed, but the switching time is unknown, and the nonlinear necessary conditions are solved by the multiple shooting method.[18] Later, they advanced their study by obtaining an optimal control strategy via a Davidenko-like homotopy algorithm and exploring the near-minimum-time control of an asymmetric rigid spacecraft with a bounded control torque.[19,20] Kumar and Zou conducted a control strategy for a pico-satellite with only a single thruster, and the thruster orientation mechanism was used which tilts the thrust vector on a two-axis gimbal.[21]

When spacecraft attitude control is obtained by exploiting internal torques generated by momentum exchange devices, gyroscopic coupling makes the issue of underactuated attitude control even more difficult.[22] With only one single-gimbal variable-speed control moment gyro (VSCMG), Yoon and Tsiotras utilized a feedback control law to achieve the control of a body-fixed line-of-sight, and a multi-stage control law was used to achieve the control objective in different situations.[23] In Ref. 14, to stabilize the attitude of an underactuated satellite under the assumption of zero momentum, two control strategies were conducted. The first one that is based on a perfect zero momentum does not need to measure the angular velocity, and it has been verified by in-orbit satellites, while the second tracks the desired angular velocity. Gui et al. studied attitude tracking of a rigid spacecraft by using two momentum-exchange actuators like reaction or momentum wheels.[24]

However, there are few papers about stabilization of space robots considering actuator failures in postcapture. Based on the immersion and invariance method, Sarras et al. designed a control strategy for stabilization of mechanical systems with an under-actuation degree larger than one.[25] For space robots, the moment of inertia with respect to the mass center would vary dramatically after capturing space debris, and often a system has an initial angular momentum due to the residual momentum of debris. These issues make the traditional control strategy unstable or even invalid.

For a space robot, motions of the base and the manipulator are strongly coupled. Dragomir et al. have conducted null reaction space control (NRSC) for planning the motion of the manipulator which causes a minimal disturbance to the attitude of the base.[26] NRSC has been verified by the flight experiment of ETS-VII, and has been applied to other unfixed-base systems, e.g., flexible-base and macro/mini robot systems, as well as humanoid robots.[27,28] Based on NRSC,

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