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Fuzzy adaptive robust control for space robot considering the effect of the gravity

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Abstract Space robot is assembled and tested in gravity environment, and completes on-orbit service (OOS) in microgravity environment. The kinematic and dynamic characteristic of the robot will change with the variations of gravity in different working condition. Fully considering the change of kinematic and dynamic models caused by the change of gravity environment, a fuzzy adaptive robust control (FARC) strategy which is adaptive to these model variations is put forward for trajectory tracking control of space robot. A fuzzy algorithm is employed to approximate the nonlinear uncertainties in the model, adaptive laws of the parameters are constructed, and the approximation error is compensated by using a robust control algorithm. The stability of the control system is guaranteed based on the Lyapunov theory and the trajectory tracking control simulation is performed. The simulation results are compared with the proportional plus derivative (PD) controller, and the effectiveness to achieve better trajectory tracking performance under different gravity environment without changing the control parameters and the advantage of the proposed controller are verified.

1. Introduction

The concept of space robot system was first proposed by the United States in the 1970's. It aimed at performing the extra-vehicular activity (EVA) by the aid of robotic manipulator in extreme environment of the space, which is hard, heavy or dangerous for people to achieve. At present, space robot is mainly used in spacecraft, satellite and international space station (ISS), especially as a main part of ISS, it is playing a crucial role in the on-orbit assembly, external maintenance and the operations of ISS.[1] As is well-known, the design, assembly and test of space robot is completed under gravity condition, however, it services under microgravity condition finally. The changes in kinematic and dynamic behavior of space robot caused by the change of gravity environment are inevitable tough for the design and verification of the control system. In fact, this problem has been attracted wide attentions in the aerospace field. Various methods for simulated microgravity environment test have been developed to debug the controls parameter and validate the function on ground, including the air floatation, suspension and neutral buoyancy primarily, which are based on the principle of gravity balance. Ranger

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test system developed by University of Maryland[2] is representative neutral buoyancy simulated test. It can realize three-dimension simulation, but the problem of water resistance cannot be solved, and it is high cost. Air floatation simulated test system provides a frictionless two-dimensional motion experiment environment. It is applied to formation flight by Stanford.[3] Suspension simulated test counterbalances the force of gravity by using gravity compensation equipment, which still belongs to the two-dimensional simulation method. It only applies to the deployment process of planar antenna or solar panel.[4] In order to ensure the on-orbit service performance of space robot, test about dynamic properties and effectiveness of controller were carried out in microgravity compared with the simulated microgravity environment. Manipulator flight demonstration (MFD) was launched in August 1997 on the space shuttle discovery. In Ref.[5] the flight experiment result was reported. The positioning errors differed from the ground test results was shown. It is presumed that these differences were due to that the ground simulated environment could not provide true microgravity, which may restrain the robot movement slightly and affect the tip position. More microgravity experiments at Tokyo Institute of Technology are introduced in Ref.[6]. The results of microgravity flight experiments show that the error of rotation position is within an acceptable range. However, there is considerable difference about the dynamic characteristic and control current compared with the ground data. In recent years, many combination simulation strategy based on the above simulated methods were proposed to eliminate the defects in simulated microgravity environment test,[7–10] but there are still problems of low fidelity and limited applicability. Given all above, the effect of gravity cannot be ignored, and cannot be solved only through the microgravity environment simulation test.

The realization of the space robot movement function depends on the control system. Therefore, the differences caused by the change of gravity environment should be taken into account when designing the controller. In particular, with the development of the space industry, space operation task is getting more and more diverse and complicate, followed by higher requirements for the accuracy and performance of the space robot system. The traditional method based on margin may bring too large output torque, it not only consume more propellant but also may degrade the positioning accuracy of manipulator terminal as well as the dynamic performance. Accordingly, this problem created by change of gravity environment should be taken on greater consideration because of the higher demand in accuracy and stability for complicated on-orbit servicing missions. For now, many dynamic analysis method and control algorithms have been proposed for trajectory tracking control of robotic system. In comprehensive consideration of flexibility of the gear tooth, mesh damping, clearance between gear teeth and mesh error, dynamics model of the large space manipulator was established in Ref. [11] by using the lumped parameter method. The concept of "system centroid equivalent manipulator" was proposed in Ref.[12]. Based on this concept, the multi-body dynamic model of a dual-arm space robotic system was developed. In Ref.[13] an adaptive control scheme was developed in the case of unknown inertial parameters for the tracking control of space robots with an attitude controlled base by combining the back-stepping design approach and adaptive control theory. In Ref.[14] a new model-free control law, called proportional plus derivative (PD) with sliding mode control law was proposed for trajectory tracking control of multi-degree-of-freedom linear translational robotic systems. In Ref.[15] a control scheme with the help of a virtual space vehicle was presented for trajectory control of a two arm rigid-flexible space robot. Li and Chean[16] used a novel regional feedback method for robot task-space control, the feedback information is employed in a local region, and the combination of regional information ensures the global convergence of robot motion. Marco et al.[17] discussed the application of the image based visual serving strategy to space manipulators and experimental results are reported. However, most of these researches so far focus on the unconstrained base,[18] the uncertainty of model,[19] the external disturbances caused by orbital environment and the high flexibility of the links and control problem in capturing task.[20,21] However, there are few researches on the self-adaptation ability of controller for the model variations due to the gravitational differences.

This paper focus on the gravity effect on the kinematic and dynamic behavior of space robot, aims to solve the problem of parameter adjustment and verification on ground through designing of control scheme. That is to design a controller applied to different models of space robot both on ground and in space without changing the structure and parameters. A fuzzy adaptive robust control (FARC) strategy is proposed for the space robot system, which can control the space manipulator to achieve good trajectory tracking effect in different gravity environments without changing the structure and parameters. The uncertain nonlinear terms of the space manipulator dynamic model caused by the change of gravity is approximated by using the fuzzy system. An adaptive control law is designed to estimate parameters online. With the help of the robust controller, the estimation error is compensated. Then the stability of the closed-loop system is proved based on the Lyapunov principle. To verify the effectiveness of the proposed method, different controllers are adopted to control two models respectively. The simulation results show that the proposed fuzzy adaptive controller can achieve better trajectory tracking performance under different gravity environments.

2. System descriptions

In this paper, two conditions of the space manipulator are discussed, so it is necessary to establish the ground alignment model and the space application model. Fig. 1 shows the

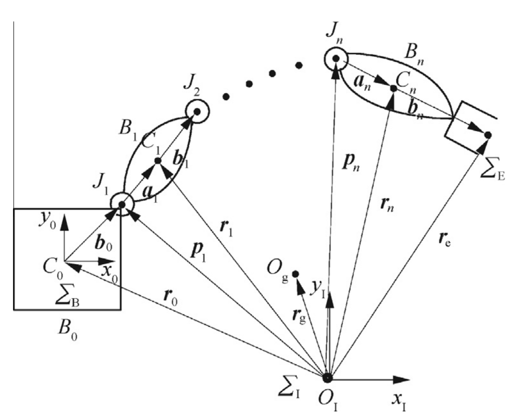

Fig. 1 *n* degrees of freedom (DOFs) free-floating space manipulator.