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Decentralized adaptive sliding mode control of a space robot actuated by control moment gyroscopes

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Abstract An adaptive sliding mode control (ASMC) law is proposed in decentralized scheme for trajectory tracking control of a new concept space robot. Each joint of the system is a free ball joint capable of rotating with three degrees of freedom (DOF). A cluster of control moment gyroscopes (CMGs) is mounted on each link and the base to actuate the system. The modified Rodrigues parameters (MRPs) are employed to describe the angular displacements, and the equations of motion are derived using Kane's equations. The controller for each link or the base is designed separately in decentralized scheme. The unknown disturbances, inertia parameter uncertainties and nonlinear uncertainties are classified as a "lumped" matched uncertainty with unknown upper bound, and a continuous sliding mode control (SMC) law is proposed, in which the control gain is tuned by the improved adaptation laws for the upper bound on norm of the uncertainty. A general amplification function is designed and incorporated in the adaptation laws to reduce the control error without conspicuously increasing the magnitude of the control input. Uniformly ultimate boundedness of the closed loop system is proved by Lyapunov's method. Simulation results based on a three-link system verify the effectiveness of the proposed controller.

1. Introduction

Space robot has been playing an important role in space service missions. Accurate trajectory tracking control is commonly required to complete the operations such as refuelling and module replacing. However, the nonlinear dynamical coupling between the base motion and manipulator arm motion makes the control very complex and incapacitates the direct application of the control algorithms for terrestrial robotic systems to space systems. To achieve superior system performance of a space robot, extensive researches focusing on control algorithms have been carried out, which are subject to different missions and problems.[1–6]

However, in general, system performance depends upon not only the active control schemes and algorithms, but also the dynamical characteristics. Traditional space robots are actuated by joint torque actuators. When the joint torque is exerted on the manipulator arm, the reaction torque is also exerted on

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the base. Such action/reaction torques definitely increase the dynamical coupling between the base and arm, and hence decrease system performance. To eliminate or reduce the dynamical coupling, the concept of "reactionless actuator" was proposed for space robots or robot-like space multibody systems. Billing-Ross and Wilson designed a reactionless drive pointing system, and summarized several advantages of reactionless actuation over traditional actuation.[7]

One typical concept of reactionless space robot is actuating the system using angular momentum exchange devices instead of joint torque actuators. In the design concept, the manipulator links are connected via free rotational joints, and the links are driven by angular momentum exchange devices, such as control moment gyroscopes (CMGs) or reaction wheels, mounted on the links. Since the actuating torques are directly exerted on the moving bodies (links or the base) and the joints are free, the action/reaction torques about the joints do not exist anymore, and consequently the dynamical coupling could be expected to be eliminated or reduced. In 1994, Osuka et al.[8] proposed a design concept of space manipulator called "torque-unit manipulator". In the design concept, each joint is free joint with one degree of freedom (DOF), and a DC-servo motor is mounted on each link to accelerate or decelerate a wheel hence to actuate the link motion. Though the concept was proposed mainly for easy maintenance, it is indeed a reactionless space robot design. Later, Peck et al.[9,10] applied CMGs to rigid robotic systems, and compared power consumption of the systems employing CMGs actuation, reaction wheel actuation and joint torque actuation. They pointed out that the CMGs actuating manipulator arm reduces the reaction torque on the base in comparison with joint actuating arm, and the system with CMGs actuation can radically outperform the other two systems in power saving for high-agility maneuvers. Utilizing the advantages of less reaction, power saving and torque amplification for CMGs, Carpenter and Peck designed a three-link mechanism for agile coelostat telescope with each link actuated by a scissored pair of CMGs,[11] and investigated power-optimal control of the system.[12,13] Refs.[14–16] presented further researches on power and energy consumption of similar system.

It is noticeable that all the reactionless systems mentioned above use one-DOF free joint as link connection. Since the joint is free, it is possible to use three-DOF ball joint to replace the one-DOF joint so that more DOF of the end effector/payload can be obtained using less joints. Such design concept has been proposed recently,[17,18] and the results in Ref.[17] verified the advantages of the system on increasing the DOF of the end effector/payload and decreasing the system dynamical coupling. Trajectory tracking control approaches were also presented in Refs.[17,18], but the control laws were based on accurate system dynamics and no system uncertainty was taken into consideration. However, uncertainties of space robot systems, such as unknown disturbances, inertia parameter uncertainty and nonlinearity uncertainty, are almost inevitable in practical use. Therefore, a robust control law against system uncertainties is required to accomplish the control mission. Sliding mode control (SMC) is considered to be an effective strategy for control of uncertain systems, and has been widely applied to robotic systems.[19–21] Conventional SMC design usually requires a priori knowledge of the upper bound on the model uncertainty; however, such a bound may not be easily determined or estimated due to the complexity of the uncertainty structure. To solve the problem, the adaptive sliding mode control (ASMC) was proposed. Yoo and Chung,[22] and Leung et al.[23] proposed sliding mode controllers in which the control gains were tuned by integral-form adaptation laws designed to estimate the upper bound of the matched uncertainty, and smoothed the controller by introducing a boundary layer to alleviate chattering. Later, Wheeler et al.[24] pointed out that the control gains in Refs.[22,23] may grow infinite in the boundary layer because the ideal sliding surface cannot always be achieved. To overcome the drawback, he improved the adaptation laws to guarantee the boundedness of both the states and estimated control gains. Besides the integral-form adaptation laws, some other algorithms such as fuzzy algorithm[25] and artificial neural network,[26] were also applied to adapt the control gain. In recent years, many approaches have been proposed to improve the performance of the ASMC, for example, the methodologies designed to reduce the overestimation of the control gain,[27,28] and the adaptive high-order sliding mode controllers aimed at low chattering and finite-time convergence.[29,30]

The objective of this paper is to propose a robust controller for the ball-joint-connected space robot actuated by CMGs. Equations of motion are firstly derived using Kane's equations for a chain-configuration space robot system with arbitrary given number of joints. Dynamics analysis shows that for the rotational motion of each link or the base, the influences of various types of uncertainties can be classified as a "lumped" matched uncertainty with unknown upper bound. Then, inspired by Ref.[24], an ASMC law is proposed which guarantees uniformly ultimate boundedness of the closed loop system. The proposed controller not only inherits the advantages of chattering free response and finite control gains from Ref.[24], but also holds the following improvements: (1) in Ref.[24], it is assumed that the model uncertainty is bounded by a linear function of the state norm, and in this paper, the linear function is extended to a polynomial function of the state norm with arbitrary given order. This expands the application scope of the controller, especially for the systems with heavy nonlinear uncertainties; (2) a general amplification function is designed and incorporated in the adaptation law, and the necessary conditions of the amplification function are also presented explicitly. The function increases the estimation sensitivity within a small given range around the sliding surface, and therefore it can reduce the control error without increasing the control input magnitude evidently. Finally, simulation results and comparison are presented to demonstrate the effectiveness of the proposed controller.

2. System description

Fig. 1 shows the space robot studied in this paper. The system consists of n rigid bodies (a base and $n-1$ links) which are connected by $n-1$ free ball joints. Each joint has three rotational DOF. A cluster (no less than three) of CMGs is installed on each body to actuate the system. The base is denoted as B_1, and the links are denoted as $B_2, B_3, \ldots, B_n$ (the links are numbered outward from the base). The joint which connects B_i and its inner body is numbered as joint i. We denote n_i as the number of CMGs installed on B_i, and call the n_i CMGs as the ith cluster of CMGs.