Acta Astronautica 101 (2014) 42–54

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Frequency-tuning input-shaped manifold-based switching control for underactuated space robot equipped with flexible appendages

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ARTICLE INFO

Article history:
Received 25 July 2013
Received in revised form
23 March 2014
Accepted 10 April 2014
Available online 18 April 2014

Keywords:
Underactuated system
Space robot
Input shaping
Flexible appendage

ABSTRACT

Underactuated control problems, such as the control of a space robot without actuators on the main body, have been widely investigated. However, few studies have examined attitude control problems of underactuated space robots equipped with a flexible appendage, such as solar panels. In order to suppress vibration in flexible appendages, a zero-vibration input-shaping technique was applied to the link motion of an underactuated planar space robot. However, because the vibrational frequency depends on the link angles, simple input-shaping control methods cannot sufficiently suppress the vibration. In this paper, the dependency of the vibrational frequency on the link angles is measured experimentally, and the time-delay interval of the input shaper is then tuned based on the frequency estimated from the link angles. The proposed control method is referred to as frequency-tuning input-shaped manifold-based switching control (frequency-tuning IS-MBSC). The experimental results reveal that frequency-tuning IS-MBSC is capable of controlling the link angles and the main body attitude to maintain the target angles and that the vibration suppression performance of the proposed frequency-tuning IS-MBSC is better than that of a non-tuning IS-MBSC, which does not take the frequency variation into consideration.

1. Introduction

A number of advanced nonlinear control techniques have been proposed to stabilize nonholonomic systems [1–5]. A space robotic system has nonholonomic characteristics if its attitude is not actively controlled by thrusters, but rather through manipulator motion only. Space robotic systems can be classified into two types: three-dimensional robots and planar robots.

Attitude reorientation problems of three-dimensional space robotic systems have been studied from the viewpoint of manipulator path planning. The surface integral approach, which was first presented for an attitude reorientation problem of a two-dimensional space robot [6], was applied to a three-dimensional robot [7]. This approach was not intended to obtain an optimal solution for attitude reorientation. In order to obtain the optimal or near optimal path parameters, several methods have been proposed, including genetic algorithms (GA) with polynomial parameterized joint trajectory [8], the particle swarm optimization (PSO) algorithm with spline approximation [9], a Newtonian method with joint angles parameterized with three parameters [10], a Newtonian algorithm with energy optimization [11], the multi-point shooting method [12],

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http://dx.doi.org/10.1016/j.actaastro.2014.04.009
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a Newton algorithm with Fourier approximation [13], and the Basis Algorithm using Ritz Approximation [14]. These studies succeeded in obtaining the optimal or near-optimal path for manipulator motion. However, the methods of [8–14] cannot be used in the implementation of real-time controllers due to their computational cost. In order to reduce the computational cost of optimization, Cerven and Coverstone [15] presented a method using averaging theory. Several feedback controllers have been proposed, including a bidirectional approach [16] and a Lyapunov-like functions approach [17]. However, the methods cited above have not been experimentally validated on the ground.

Planar space robots are not as complicated as three-dimensional space robots. Thus, real-time feedback control methods can be investigated experimentally. If the angular momentum is zero and the number of manipulator links is greater than or equal to two, then planar space robots are nonholonomic, symmetric affine systems. In this case, as stated by Brockett's theorem, no smooth time-invariant control methods that can stabilize nonholonomic, symmetric affine systems exist, even if the systems are controllable [18]. Circumventing Brockett's theorem requires non-smooth and/or time-varying control schemes in order to stabilize nonholonomic, symmetric affine systems. The problem of planar space robot reorientation has attracted a great deal of interest [6,19–28]. Mukherjee [19] used a parameterized elliptic path to form link motion of a planar space robot, and determined the parameters by steepest descent. Murray and Sastry [20] represented the motion of the foot angle and the length of a hopping robot using sinusoids and numerically determined the parameters of the sinusoids in advance. Reyhanoglu and McClamroch [21] presented a method consisting of four steps for determining the link angle trajectory. Thus, these three methods are basically feedforward control methods. Hashimoto [22,23] presented a time-varying control with average theory and a backstepping-based method. An invariant manifold has been used in several studies on the problem of planar space robot reorientation [24–27]. Mukherjee and Kamon [24] proposed the concept of “radially isometric orientation,” and established an almost-smooth time-invariant feedback control method based on this concept. Because the method in [24] suffers from a slow rate of convergence if the desired attitude and joint angles are near zero-holonomy curves, a moving manifold that has a virtual desired point was proposed in [25]. Moreover, because the method in [24] considered neither modeling errors nor time-delay in the system, an adaptive invariant manifold-based switching control was proposed to reduce the settling time and to estimate the modeling errors and time-delay in the system [26]. The effectiveness of this control was investigated experimentally [27].

However, the studies cited above did not consider attitude control problems of underactuated space robots equipped with flexible appendages, such as solar panels. Therefore, undesired large vibrations might be induced due to the link motion when the controllers cited above are simply applied to the manipulator of an underactuated space robot equipped with flexible appendages. In order to avoid the excitation of vibration of a flexible link arm on a planar underactuated space robot, Narikiyo and Ohmiya [28] tuned and checked the control parameter in advance, connected arms to flexible links with passive joints with springs and dampers, and validated their control method experimentally. However, since two arms are placed symmetrically on the main body with respect to the center of mass of the main body in [28], their model is not as complicated as a planar space robot with a serial link manipulator. In addition, the damper inserted between the arm and the flexible link is an arbitrary choice and is not always the case in a real situation, and their method is not intended to actively suppress the vibration.

In order to suppress the residual vibration on a flexible appendage attached to an underactuated planar space robot, Kasai and Kojima presented the input-shaped manifold-based switching control (IS-MBSC) [29] in which the manifold-based switching control (MBSC) [26] was combined with the input-shaping technique [30,31]. However, they did not take into consideration the dependency of the vibrational frequency on the link angles. If the time-delay interval of input-shaping is tuned in accordance with the vibrational frequency depending on the link angle, the performance of the vibration suppression will be improved. Therefore, in this paper, we propose a modified version of the IS-MBSC, which tunes the time-delay interval of the input shaper in accordance with the vibrational frequency estimated from the link angles.

Experiments are carried out in order to validate the proposed method for a planar dual-link space robot, and the proposed method is demonstrated to be capable of stabilizing the link angles and the main body attitude to the desired angles and suppressing vibration in the flexible appendage. Moreover, the control performance is shown to be better than the previous version of the IS-MBSC.

The remainder of this paper is organized as follows. In Section 2, the system model of a planar dual-link space robot and a flexible appendage is described. In Section 3, MBSC is explained. In Section 4, a combination of the MBSC and the input-shaping techniques, which is collectively referred to as IS-MBSC, is explained. In Section 5, the dependency of the vibrational frequency on the link angles is investigated experimentally and is then formulated in the form of a fourth-order function of the link angles using the response surface method. Experimental results are also presented in order to demonstrate the effectiveness of the proposed method. Finally, conclusions are presented in Section 6.

2. Model description

2.1. Planar dual-link space robot without a flexible appendage

Fig. 1 shows a schematic diagram of a planar space robot consisting of a dual-link manipulator connected by revolution joints without a flexible appendage.

Assuming that the orientation of the main body is θ, the angle of the first link (angle 1) is denoted by ϕ_1, and the angle of the second link (angle 2) is denoted by ϕ_2. The masses of the main body, the first arm, and the second arm are denoted by m_0, m_1, and m_2, respectively, and correspondingly, J_0, J_1, and J_2 are the moments of inertia of the