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Robust position and vibration control of an electrohydraulic series elastic manipulator against disturbance generated by a variable stiffness actuator☆

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ABSTRACT

This paper presents an electrohydraulic series elastic manipulator (ESEM) system containing a novel variable stiffness actuator (VSA) and a hybrid robust control. The ESEM includes a series elastic manipulator (SEM), an adjustable stiffness mechanism (ASM), and an electrohydraulic servo system (EHS). Thus, the ESEM can benefit from the advantages of the EHS, such as high-power density and a high torque-to-weight ratio. Besides, the ESEM system can use the advantages of the VSA to give the system a suitable dynamic in unknown environments as well as low energy consumption for cyclic tasks. The proposed VSA adjusts the stiffness by changing the position of the springs along the ball screw. This system can provide fast stiffness regulation in a much broader range. However, the variant characteristics of the VSA, and nonlinearities and uncertainties in the EHS, such as friction, leakages, and dependence of bulk modulus on temperature, are major challenges for the control design. The new design of a backstepping adaptive fuzzy sliding mode control (BAFSMC) is addressed in this study. It is developed via sliding mode control, backstepping technique, and an adaptive fuzzy scheme. The controller is separated into two control loops for the mechanical dynamics and the hydraulic dynamics. The SMC is embedded for each loop to reduce the system's order and to ensure that the system's state variables reach and stay on the sliding surface. The adaptive fuzzy scheme is used to replace the robust term in the control effort of the conventional SMC to get rid of the chattering phenomenon and to deal with uncertainties in the mechanical and hydraulic subsystems. The Lyapunov approach and backstepping technique are used to prove the robustness and stability of the controlled system and to derive the adaptive laws. On the other hand, a fuzzy input shaping (FIS) scheme which combines an input shaping technique (IST) and a fuzzy logic system, was proposed to minimize the residual vibration at the end effector robustly over the expected operating range of the VSA system. Numerical experiments and comparisons with some existing algorithms are presented to illustrate the theoretical results and show the efficiency of the proposed controller.

1. Introduction

Traditionally, robots are used to handle repetitive tasks precisely in complex environments. They are normally characterized by rigid links and powerful actuators which make them dangerous for human workers. Thus, to improve workplace safety, robot-human interaction becomes an interesting topic. Investigations focus on the flexible impedance properties of actuators, such as adjusting the robot equilibrium, the stiffness, and the damping. Various variable stiffness concepts were developed to reach a compromise between accuracy of execution and safe operation.

Several prototypes of VSA have been developed, such as MACCEPA 2.0 [1], MGR [2], VSRJ [3], AwAS-II [4], and 1-DOF VSA [5]. Generally, these systems combine the elastic elements, such as the spring and the flexible beam, with an adjusting mechanism. Variable stiffness actuation is based on the nonlinear deflection characteristics of the springs. MACCEPA 2.0 uses a spring and a profile disk to obtain a desired torque-angle curve, MGR adjusts the gear teeth to change the applied force on the leaf spring. AwAS-II changes the lever ratio by moving the location of the pivot. VSRJ and 1-DOF VSA use springs

Abbreviations: ESEM, Electrohydraulic series elastic manipulator; VSA, Variable stiffness actuator; AFSMC, Adaptive fuzzy sliding mode control; FIS, Fuzzy input shaping; DOF, Degree of freedom; IST, Input shaping technique; AIS, Adaptive input shaping; EHS, Electro-hydraulic servo; EHA, Electro-hydraulic actuator; SMC, Sliding mode control; BAFSMC, Backstepping adaptive fuzzy sliding mode control; ASBM, Adjustable stiffness base mechanism; DC, Direct current; MFs, Membership functions; IS, Input Shaping; BSMC, Backstepping sliding mode control; BPID, Backstepping proportional integral derivative; ZV, Zero vibration; ZVD, Zero vibration and derivative

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between the output joint and the actuators to regulate the joint stiffness in both directions of the rotational motion.

A variable stiffness series elastic actuator (VSSEA) [4] consists of two actuators. One actuator allows for stiffness tunability and the other for regulating the equilibrium position of the two-link manipulator. This mechanism increases the mechanical complexity, size, weight, cost, and integration of the system. However, [6] has proved that the performance of a lightweight rigid arm is inevitably degraded by imposing increasingly high safety constraints. Assuming that total link inertia is minimized, a possibility for performance enhancement is left with the design of compliant joint which can decouple the inertia of the actuator proper form the inertia of the last link. Another work of [7] has also shown VSA systems offer the possibility to move the load faster and more safety than other solutions based both on rigid or flexible joint. When a series elastic manipulator (SEM) contains a VSA, it can be used efficiently for lift assistance or industrial manipulators to increase workplace safety for human workers as well as provide suitable dynamics in unknown and dynamic environments [8]. The lower reflected inertia can provide safe interaction with humans [6, 7, 9]. Shocks can be absorbed by springs to prevent damage to the transmission of the actuator, which improves the safety of the robots. A stiffness controller is easily applied for VSA system and does not require using force sensors. Furthermore, the fast stiffness response of the VSA can overcome the limits of software systems during fast impacts [9]. The springs can also exchange energy with the environment to reduce the energy consumption in work that requires a high burst of power (such as the VIA joint prototype [10], a soccer-ball kicking leg [11], hopping [1] or throwing [12]). In cyclic tasks, the energy can be stored in the spring during negative work and then released when power generation is required. A study on the optimal control of a VSA hammer showed that varying the stiffness during the execution of a hammering task improves the final performance substantially [13]. Analytical results showed that a SEM with a VSA performing a hammering task can increase speed up to 30% compared to not using VSA. However, the test bench had a low torque-to-weight ratio and low energy efficiency, which can be considered as the main factors that limit the performance of actuators driven by electric motors.

By clamping a linear adjusting spring base mechanism into the second link, a new type of VSA for series elastic manipulators is proposed. This system can provide fast stiffness regulation in a much broader range. The main novelty of this proposed VSA system is using a ball screw to position the springs base, which can handle large loads and highly precise positioning. A DC motor with a high-resolution encoder is used to drive the ball screws to change the forces applied position along the second link, and the springs act as the nonlinear elastic elements. Furthermore, the spring forces acting on the motor shaft through a gearbox are not considerable, and the stiffness regulation is independent of the manipulator angular position; so, the VSA does not require a complicated stiffness controller. Besides the advantages of the VSA, the proposed ESEM can overcome the problems of the existing prototypes by replacing the electric motors with an electro-hydraulic servo system as a primary torque generator that has high power density and high energy efficiency.

Electro-hydraulic servo systems have been widely investigated for many applications, such as manipulators and aircraft. Its advantages include large force and torque output durability, reliability, and small size-to-power ratio, which is a remarkable characteristic of EHSs. When an EHS is used to control the equilibrium position, the load capacity for the repetitive task of the ESEM is expanded. However, the EHS's dynamics are very complicated because of nonlinear behaviors and modeling uncertainties, such as friction, internal leakage, external leakage, and parametric uncertainties [14]. These are challenges in developing control strategies. Various control methods have been used for trajectory-tracking control of hydraulic cylinders. The proportional integral derivative (PID) controllers [15–17] were investigated to control the position and force tracking for the electro-hydraulic actuator (EHA). The feedback linearization was used in some research work [18], but these methods did not account for the nonlinear dynamics of the cylinder and uncertain fluid parameters. Therefore, several kinds of sliding mode control (SMC) methods were adopted for the EHS system [19,20]. However, the SMC requires the knowledge of uncertainty bound which is difficult to obtain in a practical system. The chattering phenomenon is also a disadvantage in the application of the SMC [21]. Thus, adaptive control algorithms have been proposed to deal with the mentioned problems, sliding mode adaptive control [22,23], feedback linearization adaptive control [24]. Although these nonlinear control schemes showed the chattering elimination, good tracking performance and robust to uncertainties, the considered controlled plant appears to be a hydraulic actuator, which has a simpler mathematical model than the ESEM system.

To handle a complex nonlinear system, many researchers have come up with a robust control scheme which combines SMC with the backstepping approach. The combination uses the advantages of both SMC and the backstepping control, such as order reduction, the systematic and recursive design. The backstepping sliding mode control has been applied in a linear induction motor [25], quadrotor [26,27], and aeroelastic system [28]. In these systems, the actuator dynamics are typically excluded from the system behavior to simplify the control design. The control scheme has been employed in these systems without considering the actuator dynamics, and it includes a proportional control for position control and SMC for speed control. The stability and robustness of the controlled system are proved based on the backstepping technique and Lyapunov approach. In the ESEM system, the actuator dynamics are very complicated, especially because of the high nonlinearities of the cylinder friction and leakages. They can influent the dynamic characteristics and stability. Therefore, the actuator dynamics are considered in the position control for the ESEM system.

Because of the characteristics of the SEM, the first link connects to the second link through a flexible joint, the residual vibration at the end effector occurs during the trajectory tracking of the manipulator. Input shaping technique (IST), a pre-filtering reference input, was introduced by Singer and Seering [29] to eliminate the system residual vibration. IST has been used in practical systems, such as flexible manipulators [30] and ship cranes [31]. IST is a feedforward scheme, which generates shaped command based on the estimated oscillation parameters. Thus, IST is not applicable for the ESEM system containing the VSA system, because the stiffness regulation of the manipulator changes the natural frequency and the damping ratio of the vibration along with the stiffness. To overcome this disadvantage, several adaptive input shaping (AIS) schemes have been developed. E. Pereira et al. [32] used the algebraic identification method to obtain the natural frequency of the arm. J. Park et al. [33] proposed the learning input shaping technique to update the IS parameters based on magnitude and phase difference of the residual vibration. Nevertheless, these schemes require a detailed dynamic model of the plant, and the convergence rate of adaptive values is much lower than the stiffness regulation response.

Based on the above analyses, an ESEM system containing a novel VSA is proposed and discussed. The first examination of the proposed system is to control the equivalent position of the manipulator robustly to the nonlinear disturbances and uncertainties without the oscillation of the end effector. The major contributions of this study are: 1) The detail description, the nonlinear dynamical mechanism model, and the state-space model of the ESEM are introduced. 2) In the residual vibration elimination strategy, a new vibration-control method based on the concept of [26] and fuzzy technique is designed for the characteristics of the ESEM system. In this scheme, a fuzzy logic engine is embedded to tune the parameters of the IST according to the stiffness regulation of the VSA system and the cylinder actions to maintain the robustness of the residual vibration suppression. 3) In the positioning strategy, an adaptive robust controller is developed via the sliding mode, backstepping approach [34] and adaptive fuzzy scheme [35]. The controller is separated into two control loops for the mechanical