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Parametric adaptive estimation and backstepping control of electro-hydraulic actuator with decayed memory filter

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ABSTRACT

Some unknown parameter estimation of electro-hydraulic system (EHS) should be considered in hydraulic controller design due to many parameter uncertainties in practice. In this study, a parametric adaptive backstepping control method is proposed to improve the dynamic behavior of EHS under parametric uncertainties and unknown disturbance (i.e., hydraulic parameters and external load). The unknown parameters of EHS model are estimated by the parametric adaptive estimation law. Then the recursive backstepping controller is designed by Lyapunov technique to realize the displacement control of EHS. To avoid explosion of virtual control in traditional backstepping, a decayed memory filter is presented to re-estimate the virtual control and the dynamic external load. The effectiveness of the proposed controller has been demonstrated by comparison with the controller without adaptive and filter estimation. The comparative experimental results in critical working conditions indicate the proposed approach can achieve better dynamic performance on the motion control of Two-DOF robotic arm.

1. Introduction

Electro-hydraulic servo systems (EHSs) are nowadays widely used in mechatronic control engineering, due to their higher load-bearing and small size-to-power ratio [1]. One of the fundamental difficulties in hydraulic control and EHS operations is undesirable dynamic behavior of the established controller due to the ignorance of parametric uncertainties and unknown disturbance. Some parametric uncertainties are almost caused by unknown viscous damping, load stiffness, physical characteristics of valve, bulk modulus [2]. Since some unknown parametric variation may be significant in different working conditions (i.e., the phenomenon such as oil temperature variations, pressure-flow characteristics, hysteresis in flow gain characteristics, oil leakage, characteristics of valves near null) [3], many state/output feedback controllers cannot be well established to guarantee the dynamic performance of EHS. Thus, the parametric estimation is one available method to obtain unknown parameters by state observer construction integrated with other nonlinear controller. However, different from parametric uncertainties, the mainly disturbance is largely unknown torque/force disturbances caused by external loadings on hydraulic actuator. So further references have been more focused on disturbance rejection of EHS. For instance, Ref. [4] proposed a nonlinear controller in which the external load is treated as uncertain but bounded disturbance. It has been shown that the closed loop stability can directly be analyzed by the Lyapunov technique. Yao and Bu [5,6] assumed that the maximum relative uncertainty of the external load disturbance is bounded by a known value and proposed a discontinuous projection-based adaptive backstepping controller. Kim [7] presented a disturbance observer (DOB) with PI form to estimate a biased sinusoidal external load. Then, Won [8] developed a high-gain disturbance observer (HDOB) with backstepping to compensate for the unknown external load and guaranteed tolerance of the position tracking error. These references denote that the external load with wide variations is an important factor to decline dynamic response performance of a hydraulic controller, especially in some critical condition where the external load of the hydraulic actuator is close to the limitation. Therefore, to improve the dynamic behavior of EHS, various advanced control approaches were developed to estimate unknown parametric uncertainties and unmeasured disturbance.

Recently, some robust H_∞ control methods [9–12] and quantitative feedback theories [13] have been presented to overcome

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parametric uncertainties and to guarantee the robustness of a controller. A geometric control approach [14] was verified by numerical simulation to realize the dynamic tracking position of a single-rod cylinder. In the past two decades, backstepping control was widely used in EHS [15–17]. If the model of EHS is a strict feedback system [18,19], the backstepping controller based on state feedback can be well implemented. Then Yao and Bu [20] presented a discontinuous projection-based adaptive backstepping controller to estimate some unknown parameters of asymmetric hydraulic actuator. Subsequently, Guan [21,22] also constructed a parametric adaptive estimation law to guarantee the asymptotic convergence of backstepping controller. Kaddissi [23] proposed an equivalent parameter identification method by the least squares and obtained better performance than the linear controller. Ahn [24] presented an adaptive position control for a pump-controlled EHA based on an adaptive backstepping control scheme. To address some unmeasured physical states, Sun [25] proposed a perturbation observer to estimate the load pressure of single-rod hydraulic actuator. Pi [27] designed an observer-based cascade controller to estimate disturbance force in hydraulic manipulator. In addition, some output observers [26–30] were used to estimate hydraulic states with less measured information than state feedback observers. These various observers were verified in backstepping or other nonlinear control method.

However, to the best of authors' knowledge, aforementioned backstepping and adaptive controllers need to deal with some derivatives of virtual control variables which exist in backstepping iteration. These derivatives can be computed by the system state error model and parametric estimated law established in recursive controller design [18]. Since this computed process easily lead to derivative explosion, few researches are focused on the quality of these virtual control variables (i.e., data validation). If these virtual control variables are not available, especially violent, both the stability and dynamic performance of EHS will be significantly decreased. Thus, this paper presents a parametric adaptive backstepping control method based on state feedback to estimate some unknown parameters in hydraulic model. Then a decayed memory filter is proposed to compute the derivatives value of virtual control variables in the backstepping control design. The effectiveness of the proposed control is verified by a comparative experimental study.

The remainder of this paper is organized as follows. The dynamic models of EHS and external load are constructed in Section 2. The parametric adaptive backstepping controller and the decayed memory filter are designed in Section 3. Then the related experimental results are demonstrated in Section 4. Finally, the conclusion is drawn in Section 5.

2. Mechatronics plant description

2.1. Two-DOF robotic arm

The mechatronics plant is two-DOF Robotic Arm which is similar to Robotic Bigdog. The motion control of Robotic Arm is driven by an electro-hydraulic system (EHS) shown in Fig. 1. The upper arm and forearm rotate around the shoulder and elbow joint in sagittal plane respectively. The torso is fixed on the ground. The main external load is a disc on the top of forearm. The electro-hydraulic system is comprised by two servo valves, two hydraulic cylinders, two pistons, a fixed-displacement pump and a relief valve.

2.2. Dynamics of EHS

The load flow Q_L of a servo valve can be described as follows

$$Q_L = C_d w x_v \sqrt{\frac{1}{\rho}(p_s - \text{sgn}(x_v) p_L)}, \tag{1}$$

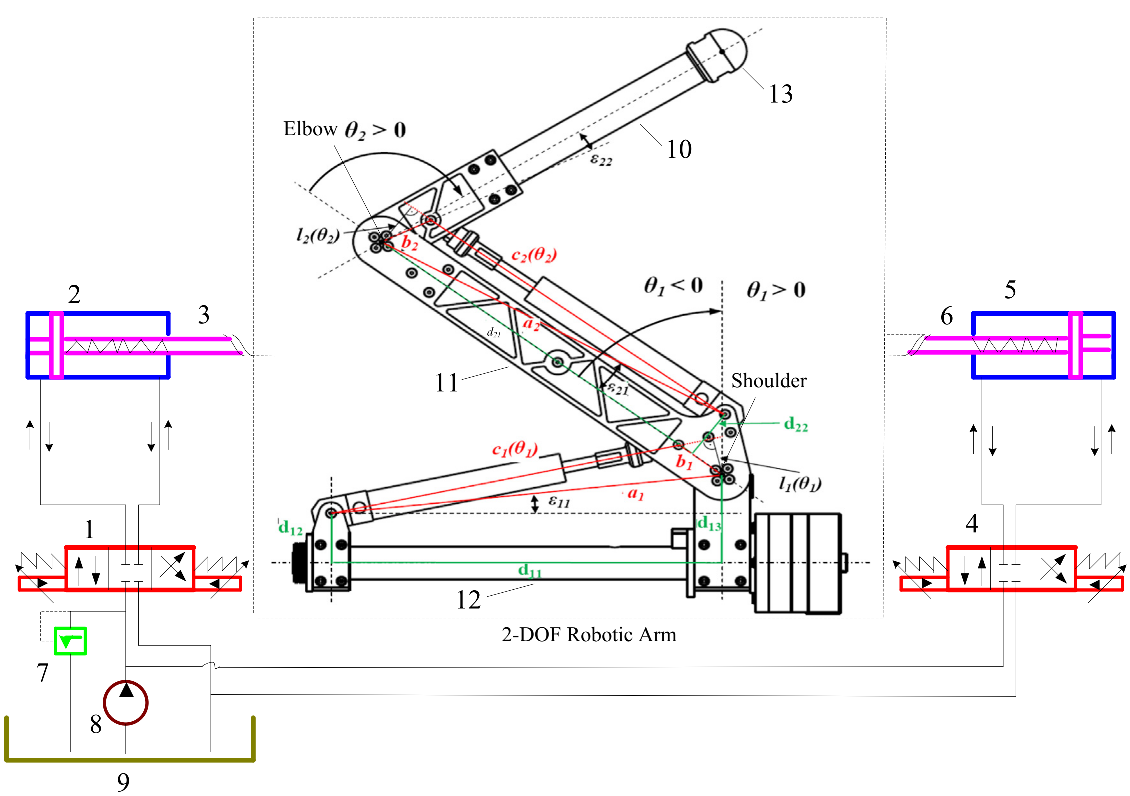

Fig. 1. The electro-hydraulic servo control mechanism of Two-DOF robotic arm (1, 4–servo valves, 2, 5–hydraulic cylinders, 3, 6–pistons, 7–relief valve, 8–fixed displacement pump, 9–tank, 10–forearm, 11–upper arm, 12–torso, 13–external load).