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Observer-based backstepping control of a 6-dof parallel hydraulic manipulator

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ABSTRACT

In this paper, a backstepping control strategy is proposed to control the 6-dof parallel hydraulic manipulator (Stewart platform) while incorporating an observer-based forward kinematics solver. Different from conventional control methods, the proposed control considers not only the platform dynamics but also the dynamics of the hydraulic actuator. One feature of this work is employing the observer-based forward kinematics solution to achieve the posture tracking goal successfully only with the measurement of actuators lengths. When designing the controller of hydraulic actuators, the friction compensation is applied to improve the performance. The stability of the whole system is thoroughly proved to ensure convergence of the control errors. Simulations and experimental results are presented to validate the hereby proposed results.

1. Introduction

The Stewart platform developed since 1965 (Stewart, 1965) is a 6 degree-of-freedom (dof) parallel manipulator. Its top platform is connected to the base platforms via six actuation links, and is moved to follow some desired attitude or posture trajectory. The parallel structure exhibits advantages such as higher force-to-weight ratio and higher positioning accuracy when compared with the serial manipulator. Due to these advantageous properties, such parallel manipulators have been used in tool machines, vehicle simulators, radio telescope, haptic devices, etc. However, the tradeoff is that its workspace is typically smaller than that of a serial manipulator, and it lacks closed-form forward kinematics solutions, that is, to obtain posture of the top platform from the knowledge of the 6 link lengths. Contrary to the case with serial manipulators, the inverse kinematics solutions of the parallel ones can be obtained relatively easily.

Hydraulic actuators are more often used in parallel manipulators than electromechanical actuators, since they can produce large forces and rapid response, and have high stiffness and durability (Merritt, 1967). The force (or torque) is proportional to current in electromechanical actuators, but the hydraulic ones do not have such property. As a result, the controller which takes into account the hydraulic dynamics should be appealing and desirable. In the researches on hydraulic servovalve, Kim and Tsao (2000) derived a linearized model for a two-stage flapper-nozzle type electrohydraulic servovalves from the intrinsic nonlinear state equations. Ziaei and Sepehri (2000) used a discrete-time linear model to model the electrohydraulic servos and actuators, and then to identify it. In the aspect of platform control, some researches (Nguyen, Antrazi, Zhou, & Campbell, 1992; Pi & Wang, 2010) consider the dynamics of actuators and developed joint-space control schemes of Stewart platforms. With force and pressure feedback, Davliakos and Papadopoulos (2008) developed a fast model-based force tracking loop to achieve tracking control with electrohydraulic servosystems. Sangpet and Kuntanapreeda (2012) used an optimization based frequency domain approach to obtain a fractional-order PI controller for force control of an electrohydraulic actuator. Besides, nonlinear control techniques have been applied to hydraulic servosystems. Along this stream, Sirouspour and Salcudean (2001) used backstepping approaches to develop a controller while employing Newton's method as forward kinematics solution to acquire the states of the platform.

In the hydraulic control issue, friction may affect the control performance and should be considered. Dahl (1976) proposed a mathematical model to describe the Coulomb friction, and applied to establish an approach to the treatment of a simple friction damped oscillator. De Wit, Olsson, Astrom, and Lischinsky (1995) also proposed a new model which captures more friction phenomena that are interest for feedback control. The friction compensation was achieved with a friction estimator in the control scheme. In another work (Kheowree & Kuntanapreeda, 2014), the observer based on the LuGre friction model is employed to compensate for the friction.

While addressing the control issue, the real-time forward kinematics solution is required. Such solutions can be categorized

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as numerical methods, analytical methods and observer-based ones. Ku (1999) and Liu, Fitzgerzld, and Lewis (1993) used the Newton–Raphson method to solve such problems subject to octahedral arrangement and with a 3–6 Stewart platform, respectively. However, the iteration scheme causes heavy computation burden. In addition, different initial conditions would affect the time of convergence. On the other hand, for using analytical approach to obtain the closed-form solutions, the works (Ji & Wu, 2001; Yang & Geng, 1998) proposed to eliminate the unknowns and form a high-order polynomial with a single unknown variable. However, such formulation is very complicated and finding all roots (eight or higher) of the high-order polynomial causes excessive computational time. Moreover, the actual solution must be chosen from the pool of multiple solutions.

Another method applies an observer to estimate the 6-dof motion of the platform. Such observer-based method is free of numerical iteration and avoids using high-order polynomials. Kang, Kim, and Lee (1998) estimated the 6-dof motion by building an estimator which can handle the nonlinearities and uncertainties of the system. Mora, Germani, and Manes (1997) proposed an observer for affine nonlinear systems by defining the observability and the diffeomorphism transformation of these systems. Then, this form of the observer was applied to the MIMO nonlinear system (Mora, Germani, & Manes, 2000). The observability given zero input together with satisfaction of an H_∞ Riccati-like inequality is proven to be sufficient for the existence of an exponential observer via Lyapunov stability analysis. With the observed posture states, Chen and Fu (2013) proposed an output feedback control for the platform. However, the scheme does not consider the nonlinear hydraulic dynamics of the actuators. Thus this method cannot achieve high performance in posture control.

In this paper, the dynamics of both the platform and the hydraulic actuator of the Stewart platform are taken into account to develop the backstepping controller. Further, to tackle the transformation between different states in the platform dynamics (task-space) and in the actuator (joint-space) dynamics, an observer-based forward kinematics solver is applied. In the proposed controller, the estimated friction was employed to compensate the friction in the hydraulic actuators. It is shown that the posture of the platform will follow a desired trajectory as closely as possible, while ensuring the overall system stability.

The paper is organized as follows. Section 2 describes the dynamics of a Stewart platform, including moving platform and hydraulic actuator dynamics. The backstepping controller design and stability analysis of the whole system are described in Section 3. Then, an observer designed to estimate the 6-dof motion is described in Section 4. The simulation and experimental results are shown in Sections 5 and 6, respectively. Section 7 gives the conclusions.

2. Manipulator and actuators dynamics

The dynamics of whole system can be divided into two parts: the rigid body dynamics of the manipulator and the hydraulic actuators dynamics. The dynamics of the parallel 6-link robot is illustrated in the first part, and the second part describes the dynamics of single hydraulic actuator.

2.1. Platform dynamics

The dynamic model of the Stewart platform (Fig. 1) possesses high nonlinearity and system uncertainties. The general dynamic model addressed in Lebret, Liu, and Lewis (1993) is described as

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{G}(\boldsymbol{q})=\boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{\tau} \quad (1)$$

where the state

$$\boldsymbol{q}=[x_p\ y_p\ z_p\ \alpha\ \beta\ \gamma]^T \quad (2)$$

is a vector with 3-axis linear translations and 3-axis rotations, $\boldsymbol{M}$ is the inertia matrix, $\boldsymbol{C}$ is the Coriolis and centrifugal force, $\boldsymbol{G}$ is the gravitational force, $\boldsymbol{J}$ is the Jacobian matrix, and $\boldsymbol{\tau}$ is the actuator force that is input to the platform dynamics.

The dynamics model can be further expressed in terms of state space representation as

$$\dot{\boldsymbol{x}}(t)=\boldsymbol{f}(\boldsymbol{x}(t))+\boldsymbol{g}(\boldsymbol{x}(t))\boldsymbol{\tau}(t) \quad (3)$$

where

$$\boldsymbol{x}=[\boldsymbol{q}\ \dot{\boldsymbol{q}}]^T$$

$$\boldsymbol{f}(\boldsymbol{x})=\begin{bmatrix} 0 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 1 \\ & \mathbf{0}_{6\times 6} & & & & -M^{-1}(q)C(q,\dot{q}) & & \end{bmatrix}_{12\times 12}\boldsymbol{x}+\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ -M^{-1}(q)G(q) \end{bmatrix}_{12\times 1}$$

$$\boldsymbol{g}(\boldsymbol{x})=\begin{bmatrix} 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \\ & M^{-1}(q)J^T(q) & & \end{bmatrix}_{12\times 6} \quad (4)$$

The output $\boldsymbol{y}$ is the vector composed of 6 actuator lengths, and can be expressed as

$$\boldsymbol{y}=\boldsymbol{h}(\boldsymbol{x})=[h_1(\boldsymbol{q})\ h_2(\boldsymbol{q})\ \cdots\ h_6(\boldsymbol{q})]^T=[l_1\ l_2\ \cdots\ l_6]^T \quad (5)$$

where $h_i(\boldsymbol{q}), i=1,2,\ldots,6$, together gives the inverse kinematics solution that transforms the platform posture to actuators lengths, namely the mapping from task space to joint space. Note that the length of the i-th actuator, l_i, can be measured by LVDT (linear variable differential transformer). It is worth mentioning that, due to the fact that such a mechanical system is passive, the systems bounded stability will be ensured if the input $\boldsymbol{\tau}$ is bounded.

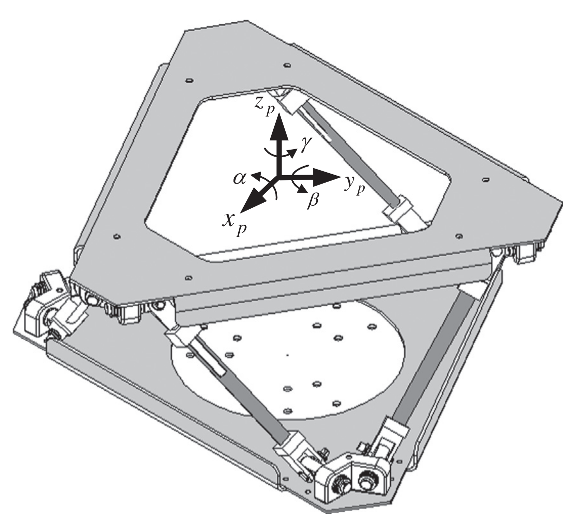

Fig. 1. 6-dof motion of moving platform.