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Incremental Nonlinear Dynamic Inversion Control for Hydraulic Hexapod Flight Simulator Motion Systems ⋆

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Abstract: Hydraulic driven manipulators face serious control problems due to the nonlinear system dynamics and model and parametric uncertainties of hydraulic actuators. In this paper, a novel sensor-based Incremental Nonlinear Dynamic Inversion controller is applied to force tracking control of hydraulic actuators of a hexapod flight simulator motion system, which together with an outer-loop motion tracking controller forms a motion control system. Due to the use of feedback of pressure difference derivatives, the proposed technique is not dependent on accurate model and parameters, which makes the controller inherently robust to model uncertainties. Furthermore, The sensor-based control approach is particularly suitable for hydraulic force tracking in existence of an outer-loop controller decoupling hydraulic-mechanic interaction term from the inner-loop dynamics. Simulation results indicate that the novel approach yields better tracking performance and confirm the greater robustness to model and parametric uncertainties compared with a traditional nonlinear dynamic invention approach.

Keywords: Motion Control Systems, Mechatronic systems, Design methodologies

1. INTRODUCTION

Stewart platforms (Stewart, 1965), also known as hexapod parallel manipulators, are adopted by most modern flight simulators used for pilot training and research as motion systems due to their high stiffness and accuracy. A moving upper platform is connected to a fixed base platform with six linear actuators that provide a motion in six-degrees-of-freedom (DOF). As high actuation forces are required by larger flight simulator motion platforms, hydraulic actuators are commonly used owning to their high loading capabilities, rapid responses and, even more important, smoothness (Koekebakker, 2001). A representation of such system is the SIMONA Research Simulator (SRS) at TU Delft (Stroosma et al., 2003), as shown in Fig. 1. The increasing fidelity requirement of modern flight simulators asks for higher performance controller for the integrated motion systems.

The Stewart platform control problem has been studied extensively during the past decades. Various model-based control schemes such as computed torque control have been proposed to deal with the highly nonlinear mechanical dynamics (Chin et al., 2008). Advanced controllers like adaptive control and robust control are also studied to overcome model and parameter uncertainty problems. However, all these techniques are difficult to be applied to hydraulic manipulators directly since hydraulic actuators are not readily available force generators, and the highly nonlinear dynamics heavily interact with the hexapod mechanics. One often applied solution to this problem

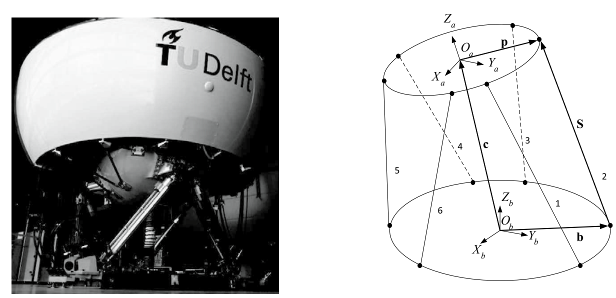

Fig. 1. A Stewart platform based motion system SRS at TU Delft and a schematic drawing

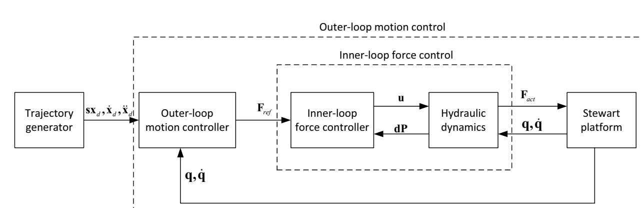

Fig. 2. Cascade control architecture for hydraulic parallel robots

is cascading the controller into a multi-loop structure as shown in Fig. 2. An inner-loop hydraulic force controller is designed to decouple the hydraulic dynamics from mechanics while generating the actuation forces calculated by a typical outer-loop robot motion controller. A high-performance hydraulic force controller is of great importance for the overall motion control performance.

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The hydraulic force control problem is challenging due to the highly nonlinear actuator dynamics (Merritt, 1967) and model uncertainties including valve opening overlaps, oil leakage and temperature-sensitive oil modulus. As pointed out in (Alleyne et al., 1998), a PID controller is inadequate for hydraulic force tracking due to fundamental limitations, which makes more advanced control schemes like nonlinear dynamic inversion (NDI) necessary. One example is the Cascade ΔP controller (CdP) introduced in (Heintze and van der Weiden, 1995) and currently implemented in the SIMONA Research Simulator at TU Delft. However, as it is an NDI-based approach, the performance of the CdP controller is strongly influenced by hydraulic parameter uncertainties. In this context, a high performance and less model dependent hydraulic force controller is required.

The novel Incremental Nonlinear Dynamic Inversion (INDI) is a less model dependent and more robust technique that has recently been adopted for various control applications (Smeur et al., 2015; Simplício et al., 2013; Sieberling et al., 2010). By calculating the increment of the control input based on the feedback of a state derivative measurement, instead of computing the total command with the modeled state derivatives with an NDI technique, the INDI controller uses less model information and is insensitive to model and parameter uncertainties. Taking advantage of pressure sensor measurement on hydraulic systems, the application of INDI on a single hydraulic actuator was recently discussed in (Huang et al., 2016a), while a detailed controller design with INDI technique on hydraulic manipulators is still to be performed.

In this paper, the INDI control methodology is adopted to design the inner-loop force tracking controller for hydraulic actuators, which together with a traditional outer-loop force computation controller form the complete control system for a hydraulic hexapod flight simulator motion system. Numerical simulations are implemented on a well-validated and fully nonlinear model of the SRS at TU Delft. Using simulation data, robustness of the applied controller against hydraulic model and parameter uncertainties are explicitly investigated and compared with an NDI based-CdP controller.

The paper is organized as follows. Section 2 discusses the model of the hydraulic hexapod motion system. Section 3 introduces the concept of the novel INDI approach, while the detailed application of INDI to the discussed motion system is presented in Section 4. Simulation results under nominal conditions and robustness tests with model mismatches are presented in Section 5. The main conclusions are then summarized in Section 6.

2. SYSTEM DYNAMICS

2.1 Motion-Base Dynamics

The Stewart platform is a 6-DOF parallel manipulator as shown in Fig. 1. A Newton-Euler formulation (Dasgupta and Mruthyunjaya, 1998) is adopted to derive the nonlinear dynamic equations in Cartesian space. The complete system dynamics are described in closed form by a second-order nonlinear differential equation, given by:

$$\mathbf{M}(\mathbf{sx})\,\ddot{\mathbf{x}} + \boldsymbol{\eta}(\dot{\mathbf{x}}, \mathbf{sx}) = \mathbf{HF} \tag{1}$$

where $\mathbf{sx} \in \mathbb{R}^6$ is the system position vector described by upper platform origin position and orientation with respect to the lower platform and $\dot{\mathbf{x}} \in \mathbb{R}^6$ is the system velocity vector described by upper platform origin velocity and angular velocity. Note that $\dot{\mathbf{sx}}$ is not equal to $\dot{\mathbf{x}}$ since the orientation is described by Euler angles and their derivatives are not angular velocity components. $\mathbf{M} \in \mathbb{R}^{6\times 6}$ is the manipulator mass matrix, $\boldsymbol{\eta} \in \mathbb{R}^6$ contains the Coriolis/centripetal terms and the gravitational term, $\mathbf{F} \in \mathbb{R}^6$ denotes the stacked actuation forces and $\mathbf{H} \in \mathbb{R}^{6\times 6}$ is the transpose of the manipulator Jacobian matrix. The readers are referred to (Huang et al., 2016b) for details.

2.2 Hydraulic Actuator Dynamics

The symmetrical hydraulic actuator driven by a typical servo valve is depicted in Fig. 3. The actuation force is generated on the moving piston with the oil pressure difference $P_{p1} - P_{p2}$ between the two separated chambers. Consider the oil flow coming into and out of the two actuator cylinder compartments, the pressure dynamics of each chamber is obtained by describing the oil compressibility with the following equations

$$\begin{aligned} \dot{P_{p1}} &= \frac{E}{V_1}\left(\Phi_{p1} - \Phi_{lp} - \Phi_{l1} - A_p\dot{q}\right) \\ \dot{P_{p2}} &= \frac{E}{V_2}\left(-\Phi_{p2} + \Phi_{lp} + \Phi_{l2} + A_p\dot{q}\right) \end{aligned} \tag{2}$$

where q is the actuator length, Φ_{p1} and Φ_{p2} are the oil flows controlled by the servo-valve, Φ_{l1}, Φ_{l2} and Φ_{lp} are the leakage flows illustrated in Fig. 3, V_1 and V_2 are the cylinder volumes of both chambers, A_p is the piston area and E denotes the oil bulk modulus.

In order to describe the pressure dynamics of Eq. (2) in a single equation, a change of coordinates is applied as in (Koekebakker, 2001)

$$\begin{bmatrix} P_m & \Phi_m & \Phi_{lm} & C_m \\ dP & d\Phi & d\Phi_l & dC \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ 1 & -1 \end{bmatrix} \begin{bmatrix} P_{p1} & \Phi_{p1} & \Phi_{l1} & E/V_1 \\ P_{p2} & \Phi_{p2} & \Phi_{l2} & E/V_2 \end{bmatrix} \tag{3}$$

Thus Eq. (2) can be transformed to

$$\dot{dP} = 2C_m\left(\Phi_m - \Phi_{lm} - \Phi_{lp} - A_p\dot{q}\right) + \frac{dC}{2}\left(d\Phi - d\Phi_l\right) \tag{4}$$

Neglecting the small second term and assuming the leakage flow to be laminar and is proportional to the pressure difference, a simplified pressure dynamics equation can be written as

$$\dot{dP} = 2C_m\left(\Phi_m - L_{lm}dP - A_p\dot{q}\right) \tag{5}$$

Under assumptions that the valve geometry is ideal with a perfectly symmetric configuration, the controlled oil supply flow Φ_m is obtained as (Merritt, 1967)

$$\Phi_m = \frac{\Phi_{p1} + \Phi_{p2}}{2} = C_d h_m x_m \sqrt{\frac{P_s}{\rho}\left(1 - \frac{x_m}{|x_m|}\frac{dP}{P_s}\right)} \tag{6}$$

where x_m is the valve spool displacement, C_d is the discharge coefficient and h_m is the width of the spool port opening.

Defining the maximum flow as $\Phi_n = C_d h_m x_{m,max}\sqrt{P_s/\rho}$, which represents the controlled flow with maximum valve