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A cascade load force control of a hydraulically driven 6-DOF parallel robot manipulator based on input-output linearization

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Abstract* - In this paper, we consider the problem of tracking control of a hydraulically driven 6-DOF parallel robot manipulator. To drive the upper moving platform, hydraulic systems composed of the six valve-controlled asymmetric pistons are used as actuators. In order to realize the trajectory tracking control of the parallel robot manipulator, a cascade control algorithm based on input-output linearization in the legspace is proposed. We applied the cascade controller, which consists of an inner loop and an outer loop, in order to separate the hydraulic dynamics from the mechanical part. Thus, the inner-loop control has the objective of controlling the actuator load force using the input–output linearization, independent of the resulting motions of the load. The outer–loop control is aimed at controlling the actuator load and rejecting external disturbance of the system. To facilitate the realization of the proposed cascade control concept, the MATLAB/Simulink model is devised. In order to show the effectiveness of the proposed cascade control algorithm, the comparative simulation results are made between proposed concept and the classical control strategy for this kind of manipulator.

***Key words*: robot manipulator, valve-controlled asymmetric pistons, cascade control, input-output linearization**

I. INTRODUCTION

The hydraulically driven parallel robot manipulator is obtained through a generalization of the mechanism proposed by Stewart [1] as a flight simulator. As shown in Fig. 1, this spatial platform mechanism consists of a fixed base platform and an upper moving platform. The six extendable legs connect these platforms. Besides greater stiffness and accuracy, these manipulators have high payload-weight ratio due to parallel linkage. Parallel linkage enables the payload distribution and averaging of the positioning error. The payload and positioning errors would be accumulated without parallel linkage. Accordingly, these types of parallel manipulators are attractive for certain applications, such as flight simulators, machine tools and force–torque sensors.

The parallel robot control strategy may be designed from two frameworks. One is to design a controller based on the legspace coordinates and the other is based on the workspace coordinates. The control strategy based on the workspace coordinates has a limitation to the real-time application due to difficultly in obtaining information on the upper moving platform. However, the upper moving platform of a parallel manipulator can move with the six desired degrees of freedom (DOF) if the lengths of the all legs are well controlled. Bearing this in mind, the control strategy study of the parallel robot manipulator rather is based on the legspace coordinates. A classical PID control technologies has been applied in practice for the control of a 6-DOF parallel robot manipulator. However, linear control techniques do not always guarantee the desired high performance of a parallel manipulator. Hence, a high-level control strategy is required to increase the control performance of the different types of actuators that are used to drive the upper moving platform, [2-3].

Hydraulic servo-system is used in a wide variety of industrial fields because of its advantages, which include rapid response, high power-to-weight ratio and compact size [4]. Thus, for the purpose of controlling the hydraulically driven parallel robot manipulator presented in this paper, we will use a hydraulic servo system. Dynamics of the hydraulically driven 6-DOF parallel robot manipulator consist of two parts. One is mechanical dynamics and the other is hydraulic dynamics, see [5]. Therefore, the designed controller should take into account not only the mechanical dynamics, but also the hydraulic dynamics using the cascade control method, see [5-8]. We decided to implement the feedback linearization for controlling the actuator load force, independent of the resulting motions of the load. Feedback linearization has attracted great research interest in the last two decades, [9]. The general idea of the approach is to transform non-linear system dynamics algebraically into a linear one, so that linear control techniques can be applied. This differs entirely from conventional linearization, in that feedback linearization is achieved by exact state transformations and feedback, rather then by linear approximations of the dynamics. MATLAB / Simulink model is devised to facilitate the realization of the proposed method. The simulation results for the robot manipulator are presented to show the effectiveness of the approach.

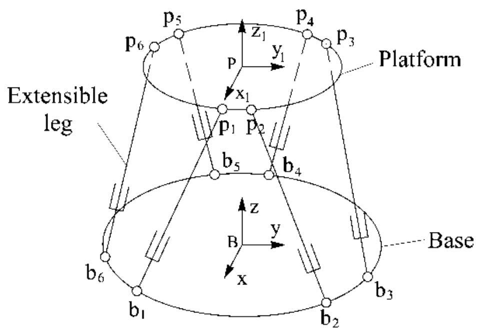

Fig.1. Schematic diagram of a 6-DOF parallel robot manipulator (modified from [8])

II. MODEL OF THE HYDRAULIC ACTUATOR FOR A 6-DOF PARALLEL ROBOT MANIPULATOR

For drive upper platform, hydraulic system composed of the six cylinders, controlled by servo valve, are used. Schematic view of double acting, asymmetric hydraulic cylinder with connected four-way spool valve is shown on Fig.2.

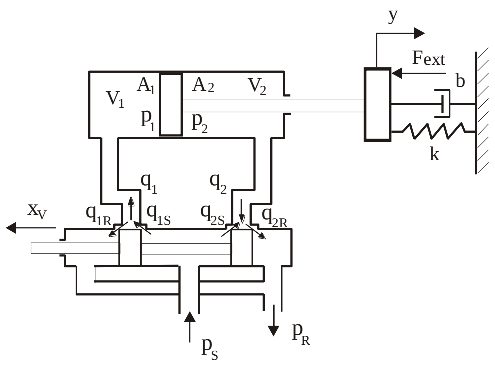

Fig. 2. Schematic diagram of a hydraulic actuator

Hydraulic systems are often employed in high performance applications that require fast response and high power. These applications include high bandwidth control position and force. The problem is that these systems contain non-smooth nonlinearities caused by variable geometry and variable working conditions. For nonlinear analysis of performance and control of the hydraulic systems we need appropriate model.

On the physical concept level of modeling, using bond graph notation, a unified model of four-way spool valve is shown on Fig.3, [10].

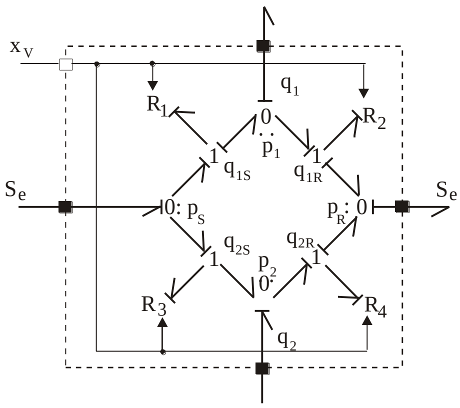

Fig. 3. Unified model of four-way spool valve (modified from [10])

The valve is used as a distributor of hydraulic energy goes from the pump to the cylinder and reservoir. Model interface consist of four energetic and one signal port. Each of them represent variable orifice modulated by signal x_v. Constitutive relation of energy dissipation mechanism is given by:

$$q = C_d w \sqrt{2/\rho}\,\mathrm{sgn}(P_1 - P_2)\left|P_1 - P_2\right|^{1/2} u(x_v, \varepsilon, L) \qquad (1)$$

where $u(x_v, \varepsilon, L)$ denotes saturation function:

$$u(x_v, \varepsilon, L) = \begin{cases} 0 & x_v \le -\varepsilon \\ x + \varepsilon & -\varepsilon < x_v < L - \varepsilon \\ L & L - \varepsilon \le x_v \end{cases} \qquad (2)$$

C_d represents valve discharge coefficient, w denotes valve area gradient, ρ denotes fluid mass density, P_1 denotes upstream pressure, P_2 denotes downstream pressure, x_v denotes valve spool position, ε denotes spool lapping parameters, L denotes valve port opening.

Double acting, asymmetric hydraulic cylinder bond graph is shown on Fig.4.

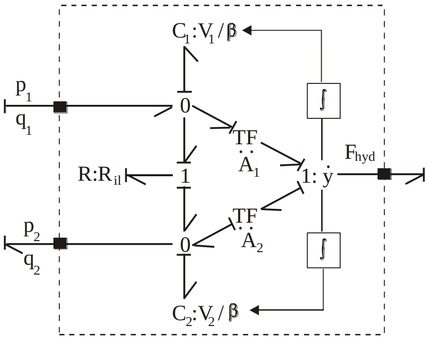

Fig. 4. Hydraulic cylinder bond graph

The primary function of hydraulic actuator is conversion of hydraulic energy into mechanical. Because of different effective area of the head side and rod side of the piston, two transformers ($TF : A_1$, $TF : A_2$) are used. Fluid compressibility in cylinder chamber is characterized by C storage mechanism. Constitutive relation of this mechanism is given by equation:

$$p_i = -\beta \int \frac{q_i}{V_i} dt\,, \quad i = 1,2 \qquad (3)$$

For hydraulic fluids, the bulk modulus β has a nearly constant value. However, the chamber volume changes over time due to piston motion. For these reasons modulation signals are used. Internal leakage flow across the chambers is modeled by dissipation mechanism ($R : R_{il}$)

$$q_{il} = R_{il}(p_1 - p_2) \qquad (4)$$

The actual position of the piston (upper moving platform) depends on the dynamic properties of the loads acting on the piston. Overall load acting on piston is modeled by mass-spring-damper system shown on Fig. 5.

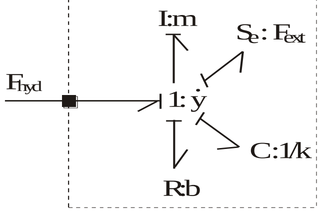

Fig. 5. Model of overall load acting on piston

III. CONTROL ALGORITHM

As mentioned in the introduction, it is necessary to design a control algorithm based on the legspace coordinates of the hydraulically driven parallel robot manipulator. Besides the mechanical dynamics, the designed controller should also take into account the hydraulic dynamics. In the 6-DOF hydraulically driven parallel robot manipulator, six hydraulic cylinders act on the same load (the upper moving platform) so that the outputs and control of the six actuators affect one another. Therefore, the loads of the six actuators are coupled. The coupling, which is embedded in one of the actuators, makes this actuator a variable load system with a time-dependent external disturbance. Hence, the designed controller should be robust to parameter perturbation, be able to reject the external disturbance and sufficiently take into account the hydraulic dynamics. The schematic diagram of the cascade control for the single hydraulic actuator, based on the input-output linearization, is shown in Fig. 6.

As depicted in Fig. 6, the cascade F_L control consists of two loops. First, the inner-loop control, which is the actual actuator control loop, has the objective of controlling the actuator pressure–difference–force F_L using the input–output linearization, independent of the resulting motions of the load. This means that it gives the actuator the character of a force generator. Second, the outer–loop control is concerned with the stabilising control of the actuator load and the compensation of external forces F_{ext} .

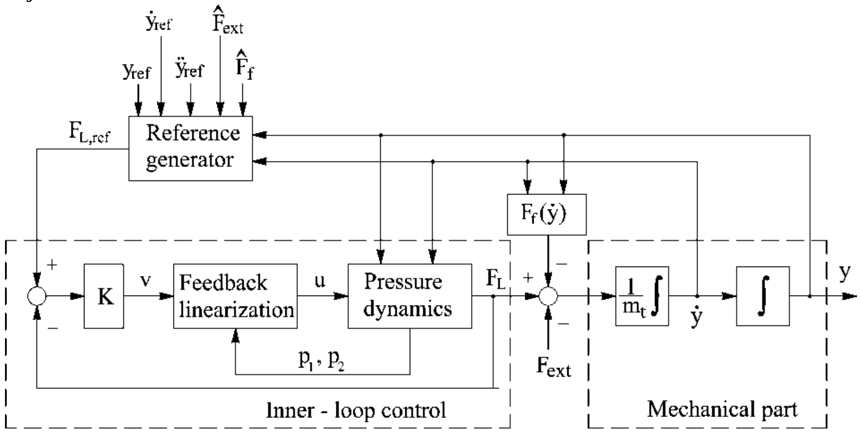

Fig.6. Structure block diagram of the cascade control based on input output linearization (adjusted from [9])

The intuitive and simple basis of the input-output linearization approach to non-linear control design is to find a direct relation between output from the subsystem "pressure dynamics" F_L and the control input u , see Fig. 6. To generate such a direct relationship, the output equation

$$F_L = A_1(p_1 - \alpha p_2), \quad \alpha = A_2/A_1 \tag{5}$$

is differentiated so often as the input u does not explicitly appear. Once an explicit relationship

$$\begin{aligned}\dot{F}_L &= -A_1^2\left[\frac{\beta}{V_1} - \alpha^2\frac{\beta}{V_2}\right]\dot{y} - \left[\frac{\beta}{V_1} + \alpha\frac{\beta}{V_2}\right]c_L(p_1 - p_2) + \\ &+ A_1\left[\frac{\beta}{V_1}c_{v1}\sqrt{|p_s - p_1|} + \alpha\frac{\beta}{V_2}c_{v2}\sqrt{|p_2 - p_R|}\right]u = \\ &=: v\end{aligned} \tag{6}$$

between u and F_L is obtained, the corresponding output derivative is set to the new input v , also termed virtual or artificial control input, and the relationship is solved with respect to u to give the control law for input-output linearisation. In (6) c_{vi} denotes the flow coefficient ($i = 1, 2$) while c_L represents the internal leakage flow coefficient. The area ratio of the asymmetric piston is $\alpha = A_2/A_1$, where A_1 is the effective area of the head side of the piston and A_2 is the effective area of the rod side of the piston. More details about interpretation of the control low can be found in [9].

Using this linear relationship, the system output can easily be made to exhibit the desired behaviour. For this, the virtual signal v can be selected to be an appropriate function of F_L and $F_{L,ref}$.

In other to achieve position tracking, the desired force should be chosen to be, [11]:

$$F_{L,ref} = m_t\ddot{y}_{ref} - k_v(\dot{y} - \dot{y}_{ref}) - k_p(y - y_{ref}) + \hat{F}_f(\dot{y}) , \tag{7}$$

where $\hat{F}_f(\dot{y})$ is an estimate of friction forces in the cylinder, combined with the simple proportional feedback (with adjustable gain K),

$$v = K(F_{L,ref} - F_L) \tag{8}$$

to give the first–order closed–loop behaviour

$$\frac{1}{K}\dot{F}_L + F_L = F_{L,ref} \ . \tag{9}$$

IV. SIMULATION RESULTS

To facilitate the realization of the proposed cascade control concept, the MATLAB/Simulink model is devised. In order to verify the effectiveness of the proposed control algorithm, the comparative study is made between proposed concept and the classical control strategy for this kind of manipulator. Thus, the proposed controller is compared with a well-tuned PID controller, which is widely used in practice.

Figures 7 and 8 present position tracking of one of the extensible actuators for the following reference trajectories $y_{ref} = 400 + 3\sin(2\pi t)\ mm$ and $y_{ref} = 400 + 3\sin(4\pi t)\ mm$, respectively. The positioning errors which were made at above cases can also be seen.

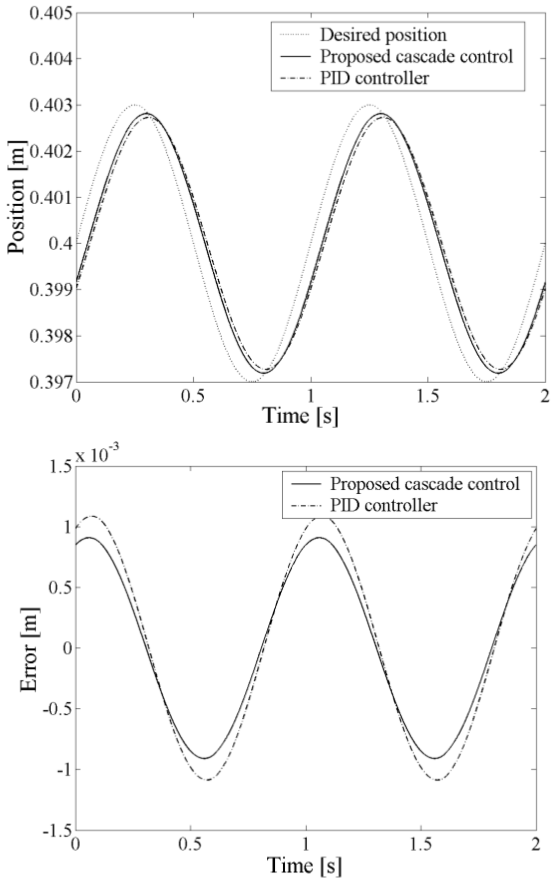

Fig. 7. Position tracking (1Hz) of one of the extensible actuators

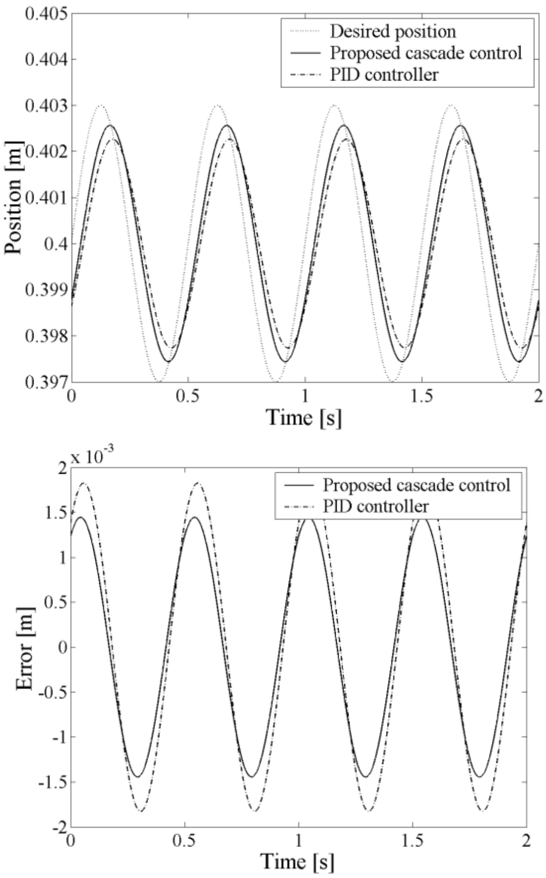

Fig. 8. Position tracking (2Hz) of one of the extensible actuators

V. CONCLUSION

In order to realize trajectory tracking of the 6-DOF parallel robot manipulator, we proposed a cascade control strategy based on the feedback linearisation in the legspace. Detailed simulation results of one of the actuators show that the developed cascade controller based on the input-output linearisation outperforms the well-tuned PID controller and exhibits satisfactory tracking performance. In order to test the tracking performance of the robot manipulator, simulation results from remaining actuators would have to be conducted. Compared to the classical PID controller, where is necessary to perform appropriate adjustments in a small range for a favourable performance, there is no modification for the proposed cascade controller, due to its high robustness.

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