Constrained MPC for Bilateral Control of Hydraulic Stewart Master-slave System

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Abstract. A master-slave system consisting of a hydraulic Stewart mechanism is developed. This system can be used for grinding complex curved surfaces while keeping the operator away from the harmful dust produced. to prevent the upper platform from moving in the wrong direction because of the limitations of the hydraulic drive capability, a constrained model predict control (MPC) controller is developed for the slave platform. Experiments are performed to verify the performance of the controller

Introduction

The Stewart mechanism is a spatial platform mechanism. It consists of a fixed base platform and an upper moving platform, which are connected by six extendable legs. These manipulators have greater stiffness, accuracy, and payload-weight ratio due to parallel linkage[1].

Force-feedback joysticks actuated by electromotors do not provide adequate position accuracy and feedback force stiffness; therefore, studies are now focusing on hydraulic actuators. Yamada and Kudomi [2,3,4] used a single cylinder as the master hand and a virtual spring as the slave hand to validate the function of algorithms for hydraulic force feedback systems such as force reflection type and force symmetry type in a hydraulic force feedback manipulator. Based on two-port network theory. Hou proposed a strategy-switching control for hydraulic force bilateral servo system when catching high rigidity objects[5].

An important problem for hydraulic Stewart master slave system is that the upper platform may move in an undesired direction if excessive force is applied to any cylinder. To solve this problem, this study develops a model predict control (MPC) controller with a force constraint.

The Master-slave System

The Overall System

Figure.1 shows the proposed hydraulic Stewart force feedback master-slave control system. The upperpart shows the master-slave teleoperation force feedback control system and the lower part, the force-feedback joystick based on the hydraulic Stewart mechanism for the master site. In some experiments, the joystick can also be used as the plant for the slave site.

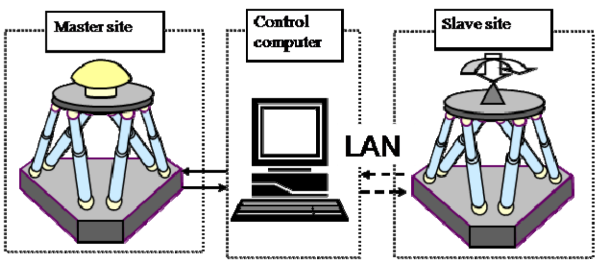

Figure.1 Hydraulic Stewart master-slave system

The feedback master-slave control system for the hydraulic Stewart force consists of the operator, master and, communication links, slave and, and external environment.

Master Slave Control

Figure.2 shows the overall control architecture of the system. The force Fm, which is applied by the operator to the master hand, is detected by force sensor to drive the movement of the force display. Mean while, the master hand needs to display the reaction force that applied to the environment force.

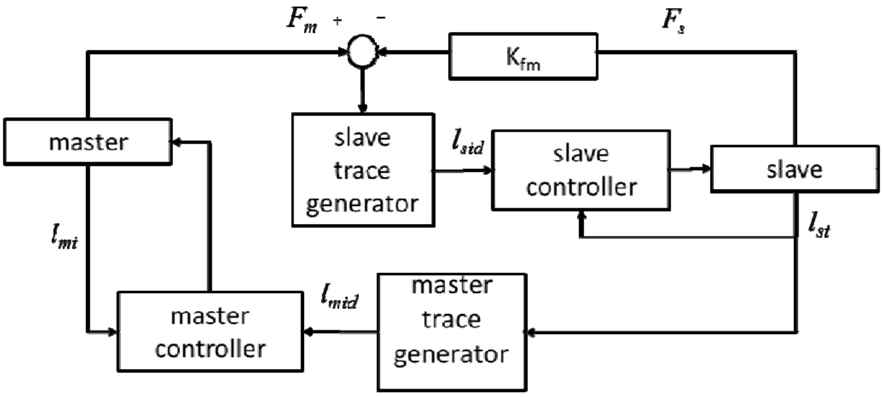

Figure.2 The master-slave controller

When operator pushes the master hand, the slave hand tracks the movementfrom the trace generated according to the operator and environment force, meanwhile the master hand tracks motion of the slave upper platform. Thus this is a slave driving force feedback control.

Slave Controller Design

Problem Description

Consider the following scenario: force vector F of uncertain magnitude but definite direction acts on a point or on the upper platform of the slave Stewart mechanism. A cylinder reaches its force limitation, but other cylinders continue to move forward, and therefore, the upper platform moves in an undesired direction. Such a scenario should be prevented before the force exceeds the limitation.

Control Framework

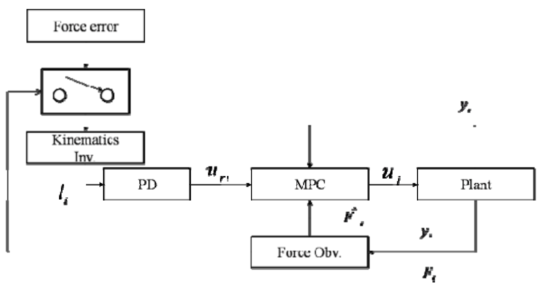

Figure.3Constrained MPC for slave cylinder

To deal with such a scenario, a constrained MPC controller is used in the system in consideration of the output force constraint.

Figure.3 shows the slave control system with a constrained MPC. The desired cylinder length lid is calculated based on the force error by the slave platform's inverse kinematics. Based on lid and the predicted force Fip, the MPC is applied to obtain the desired control input ui. When the force of any cylinder exceeds its limit, switching is performed to avoid using the upper platform to move forward. Then, the MPC controller becomes a position conservative controller.

MPC for Hydraulic Cylinder

A state-space-based multi input single output (MISO) MPC controller is used with the position, force, and uncertain force as an input. This study introduces the state-space model of the hydraulic servo cylinder, optimal cost function, and its constraint. The MPC controller has been described in [6].

As described in [7], the entire dynamics can be expressed in a state-space form as

$$\begin{aligned} x &= [x_1, x_2, x_3]^T = [x_L, \dot{x}_L, P]^T \\ \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{1}{m}(A_1 x_3 - b x_2 - F_d) \\ \dot{x}_3 &= \frac{\beta_e}{V_1}[-A_1 x_2 + k_q k_a \sqrt{\Delta P_1} u - C_t x_3] \end{aligned} \tag{1}$$

Where β_e is the bulk modulus of the fluid; b, the damping coefficient; F_d, the push force on the cylinder rod; A_1, the area of the cylinder rod, m, the mass; k_q, the flow gain coefficients of the servo valve; k_a, the servo valve amplifier gain; and u,the servo valve control input signal. C_t is the internal leakage coefficient, V_1 $(x_L)$and $V_2(x_L)$are the total fluid volumes of the two sides of the cylinder, and P_1 is the pressures inside chamber 1 of the cylinder.

In equation (1), the servo valve is treated as a proportional loop.

The cylinder model is expressed by a MISO state-space model as

$$\begin{aligned} \dot{X} &= AX + Bu \\ Y &= CX \end{aligned} \tag{2}$$

where A,B, and C are the differential elements derived from the space-function-based plant model.

$$u = \begin{bmatrix} F_{idu} & F & \xi \end{bmatrix} \tag{3}$$

Where F_d is the desired dynamic force; F_{idu}, the desired force of the cylinders; and ξ, the uncertain force input.

The estimation error of the load force $\tilde{F}_d$ is given as

$$\tilde{F}_d = F_d - \hat{F}_d \tag{4}$$

where $\hat{F}_d$ is the force from the Stewart dynamic force observer.

$$\hat{F}_d = (J_f^T)^{-1}(M\ddot{X} + V\dot{X} + G) \tag{5}$$

where X is the vector of the platform generalized coordinates and F, that of the generalized applied force of the actuators. M is the Stewart mechanism mass matrix, Vcontains Coriolis and centripetal terms, and G represents gravitational effects. Jf is the force Jacobian matrix of the system.

The optimal cost function is

$$\min J(k) = \sum_{i=0}^{\infty}(PX^2 + RU^2) \tag{6}$$

where P and R are the coefficient matrixes. X is the position output and U, the control input. The cost function may perform a tradeoff between the position accuracy and the control input. The constraint includes the current input and force input constraint.

$$U_{\min} < U_c < U_{\max},$$
$$F_{\min} < F < F_{\max} \tag{7}$$

Experiment

Table.1 Parameters of Stewart platform

Quality of upper platform	0.5kg
Circumcircle radius of hinge point of upper platform	0.2m
Circumcircle radius of hinge point of lower platform	0.3m
Quality of cylinder rod	0.8kg
Quality of cylinder sleeve	1.2kg

To validate the correctness of the MPC, we use a pair of force-feedback joysticks in an experiment. As is shown in Figure.4, the operator controls the master joystick to actuate the slave platform to move and make contact with a spring as a soft collision.

Figure.4Experimental system for springcollision

Figs.5, and 6respectively show the results for the PD controller and the constrained MPC controller. In this experiment, the positive and negative cylinder actuator force limit is set to 16 and 9N, respectively. The spring stiffness is 10000N/m.

(a)

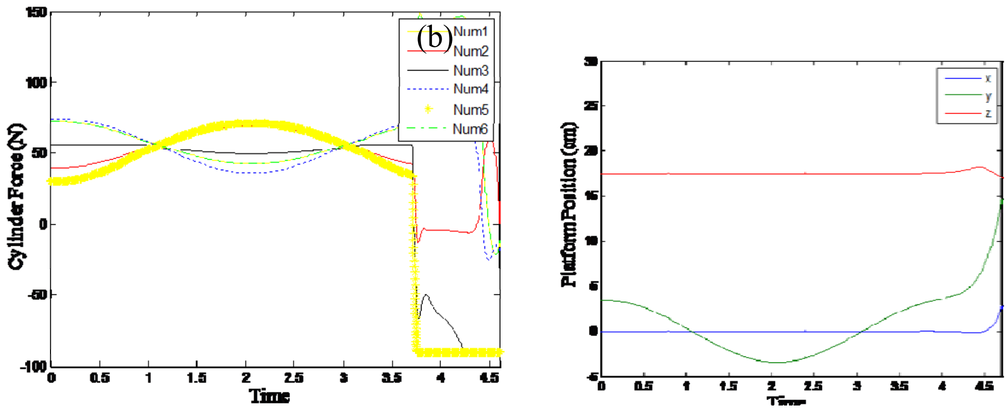

Figure.5Cylinder force (a) and platform position (b) for PDcontroller

(a)

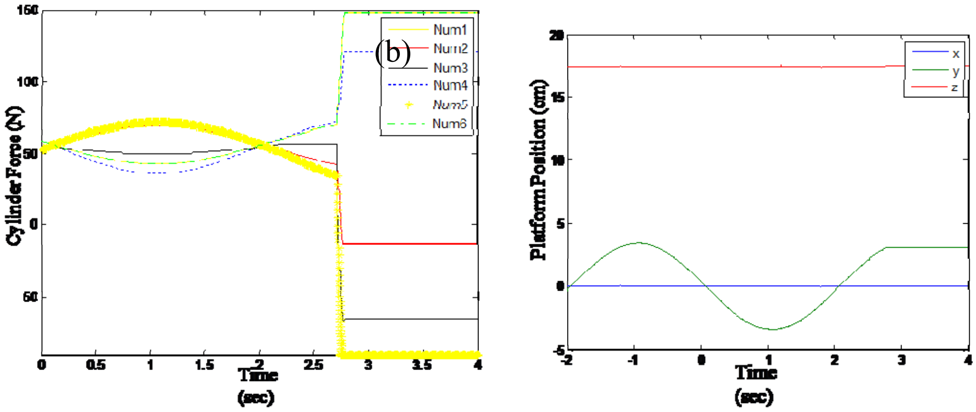

Figure.6Cylinder force (a) and platform position (b) for constrained MPC controller

The result shows that when the driving force exceeds the cylinder force limit, the PD controller cannot provide sufficient position accuracy and moves in an undesired direction, because the environment force exceeds the capability of the Stewart platform. In contrast, the constrained MPC controller uses the switch function to stop the motion of the platform when the actuator force of any cylinder reaches its limit, thus preventing the upper platform from moving in the wrong direction.

Conclusion

This study addresses the control of a hydraulic Stewart system. A constrained MPC is used to ensure position accuracy and prevent the upper platform from moving in the wrong direction. A simplified state-space model for the hydraulic servo cylinder is applied as a reference plant in the MPC. Experiments are performed to verify the performance of the algorithms. It is found that load disturbances are the main external disturbances in parallel robot manipulators, and they always greatly impact the system performance. More research work is required in the future.

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References

[1] I.Davliakos, and E. Papadopoulos.Model-based control of a 6-dof electro hydraulic Stewart–Gough platform. Mechanism and Machine Theory. 43(2008)1385-1400.

[2] Kudomi S., Niwa Y.,and Yamada H. Development of a hydraulic masterslave system for tele-manipulatorics[C]. Proc. 1th FPNI-PhD Symp.Hamburg 2000, Paper no. 467-474.

[3] H. Yamada.and T. Muto.Development of a parallel link type force display,(Force feedback of a 1DOF force display by means of hydraulic servo system) Proc. of 7th Symp. on Fluid Control and Measurement.(1999)17-20.

[4] Kudomi S. Niwa, Y. Yamada, H.. Development of a parallel link type force display[C]. Proc. Spring Conf. of Fluid Power System.Osaka,(1999) 37-39.

[5] Hou J., and Zhao D., Strategy-switching Control for Hydraulic Force Bilateral Servo System when Catching Objects.Transactions of the Chinese Society for Agricultural Machinery. 43(2012)190-211.

[6] Y. Pi.andX.Wang. Trajectory tracking control of a 6-DOF hydraulic parallel robot manipulator with uncertain load disturbances. Control Engineering Practice. 19 (2011) 185–193.

[7] G. Li. Intelligence control and its matlab realization. Publishing house of electronicsindustry.BeiJing, 2005.