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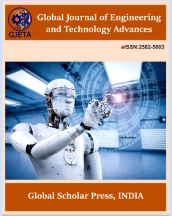

(RESEARCH ARTICLE)

Trajectory tracking performance of modal space decoupled controller for six Degree of Freedom parallel mechanism (6 DOF pm)

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Abstract

The paper presented the trajectory performance of the Modal Space Decoupled Controller (MSDC) and the conventional joint space controller. Phase retarding and amplitude fading were chosen to evaluate how well the modal space decoupling controller can follow a trajectory. The responses of sinusoidal inputs along six directions surge, sway, heave, roll, pitch, and yaw were given. The result indicates that the modal space decoupling controller has better tracking performance when compared to conventional PID controller. For the conventional joint space controller (CJS), the phase retarding for the linear and angular motions motion attains maximum value at 40.90º and 23.98º respectively. The maximum phase retarding is at 22.84º in linear motions and 0.975º in angular motions for the modal space decoupling controller. The amplitude of the conventional controller fades at 0.54dB in linear motions and 0.47dB in angular motions, while for the modal space decoupling controller, the amplitude fades at 0.1696dB in linear motions and 0.082dB in angular motions. Subjecting the two controllers to the tracking of a desired circular combined motion of surge and sway, the predefined circular trajectory was well tracked much more by the proposed MSDC than the CJS.

Keywords: Six Degree of freedom; Modal Space; Controller; Tracking; Trajectory

1. Introduction

There have been various studies on six degrees of freedom parallel mechanism (6 DOF PM), Stewart Platform due to its advantages over the serial mechanism. These advantages are: better accuracy, large mechanical advantage, higher payload to weight ratio, less sensitive to joint disturbances, higher force-to-weight, stiffness and positioning accuracy. They have been used in various fields such as space docking, armored tank, flight, submarine and earthquake simulation, and machine tools etc [1-3]. The mechanism has the disadvantages of smaller workspace, complex command, and lower dexterity due to high coupling effects. The coupling effects are caused by its highly interactive system where the elongation of one of the six hydraulic cylinders induces a reaction forces in all other cylinders. The position and attitude of the moving platform varies with different effective mass, thereby, changing the system characteristics in each DOF [1-5]. The coupling of the system makes motion planning and control difficult, because changing one input to control its corresponding output will also affect other outputs. Hence, it is important to study coupling effects and decoupling control strategies for the improvement of the control performance.

Various authors have studied coupling effects and decoupled control strategies. Ogbobe et al [6-9] analyzed the coupling effects between DOF and actuators by applying a singular value decomposition to the properties of joint space inverse mass matrix using a transformation matrix, product of transposed Jacobian matrix and an orthogonal unitary matrix. They provided useful design information to mechanism and controller designers to assess from conception the coupling effects between DOF in respect of the requirement for a particular application. Decoupling the functional requirements

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of 6 DOF PM is becoming a basic design principle with certain advantages such as decoupled motion characteristics, selective actuation for different tasks etc [6-9]. In the past few years, various types of decoupling control strategies have been proposed in literatures [11–15]. McInroy and McInroy et al. [16-17] have proposed two decoupling algorithms by combining static input-output transformations with hexapod geometric design. Chen and McInroy, [17] provided and formulated a modified model that loosened and removed severe constraints of prior decoupling methods on the allowable geometry and payload. Thus, they greatly expanded the applications, and then proposed a decoupled control method applicable to flexure-jointed hexapods for micro precision and vibration isolation. The flexure jointed hexapod has very limited stroke and no need to include typical position dependent nonlinearities. The above control methods also can be extended and be applied to controlling hydraulic controlled 6 DOF PM, with inclusion of pose dependent nonlinearities and dynamic of hydraulic actuators.

The work of Hoffman [18], has shown that the hydraulic controlled Stewart platform in any positions has six independent directions, a set of eigenvectors, with the characteristics as described for the one degree of freedom system, so it is possible to apply the methods and theories well suited for single DOF hydraulic mechanical systems to analyze and design the Stewart platform with the combination of decentralized feedback. but without consideration of the coupling effects between all the actuators, only the resonance peaks of the lower eigenfrequencies of six rigid modes can be attenuated. The peaking points of other relative higher eigenfrequencies will be over damped [18], resulting to a controlled system with a bandwidth corresponding to the lowest eigenfrequency [18]. This also exists in dynamic pressure feedback and is a significant drawback to its applications. The study by Ogbobe et al [9] investigated the use of dynamic pressure feedback for the control of hydraulic controlled 6 DOF PM considering the dynamic coupling effects. The approach was to design and tune the dynamic pressure feedback based on the modal space decoupling control strategies. The motivation of using modal space decoupling control strategy is that each degree of freedom can be almost tuned independently and their bandwidths can also be raised near to the eigenfrequencies [9]. The purpose of the present paper is to evaluate tracking performance of the effects of the modal space and conventional joint space controllers. It is with a view to evaluate how feasible the controller will follow a trajectory. This section will develop modal space decoupling control strategy and applied to a model of the hydraulically driven 6 DOF PM. The controller took into consideration the coupling effects of the system which usually are neglected in conventional joint space controller.

2. Plant modelling

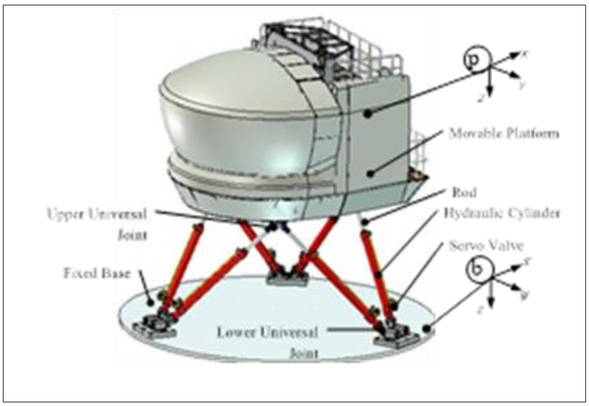

Figure 1 Schematic view of a hydraulic controlled 6 DOF parallel mechanism

The 6 DOF parallel mechanism for our study is a hydraulic controlled 6 DOF closed kinematic chain mechanism with two bodies connected by the six extensible legs consisting of a fixed base {b} and a moveable platform {p} with six hydraulic actuators supporting it as shown in figure 1, $\mathbf{a}_\mathrm{i}$ denotes the 3×1 vector of upper joint center point in body axes, $\mathbf{b}_\mathrm{i}$ represents 3×1 vector of the lower joint center point in fixed base frame , and the sub index *i* is the actuator number. At neutral pose the body axes {p} attached to the movable platform are parallel to and coincide with the inertial frame {b} fixed to the base with its origin at the geometric centre of the base platform.

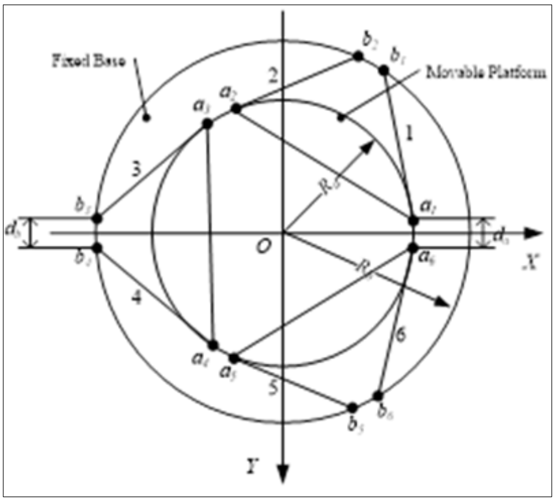

Figure 2 Top view of 6 DOF parallel mechanism

The equations of motion of a typical 6 DOF parallel mechanism considered as 14 rigid bodies are derived using a Kane's method [19] as

$$\mathbf{M}(\bar{\mathbf{q}})\ddot{\mathbf{q}}+\mathbf{C}(\bar{\mathbf{q}},\dot{\mathbf{q}})\dot{\mathbf{q}}+\mathbf{G}(\bar{\mathbf{q}})=\mathbf{J}_{\bar{\mathbf{q}}}^{\mathbf{T}}(\mathbf{q})\mathbf{f}_{\mathbf{a}} \quad (1)$$

$\bar{\mathbf{q}}=[\mathbf{x} \quad \mathbf{y} \quad \mathbf{z} \quad \boldsymbol{\varphi} \quad \boldsymbol{\theta} \quad \boldsymbol{\psi}]^{\mathbf{T}}$, denotes the 6×1 vector of the platform position with respect to the fixed base frame, and contains translation and Euler angles. $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are the 6×1 platform velocity vector and acceleration vector respectively, and both contain translation and angular components. $\mathbf{f}_{\mathbf{a}}$ is the 6×1 vector of actuator output forces. $\mathbf{M}\bar{\mathbf{q}}$ represents the 6×6 mass matrix found in the base frame, considering the inertial effects of the actuators, $\mathbf{C}(\bar{\mathbf{q}},\dot{\mathbf{q}})$ is the 6×6 Coriolis/centripetal coefficients matrix, $\mathbf{G}(\bar{\mathbf{q}})$ is the gravity terms. Details of the above expressions have been described in detail by [2]. $\mathbf{J}_{\mathbf{l},\bar{\mathbf{q}}}$ is 6×6 Jacobian matrix relating the platform movements to the actuators length changes in joint space. Neglecting Coriolis/centripetal and gravity terms in Eq. (1), gravity will be compensated while Coriolis/centripetal will be treated as external disturbances in the Matlab/Simulink simulation model. Kinematics and dynamics analysis of the 6 DOF parallel mechanisms has been well established and can be found in several literatures [4,6-12].

3. Dynamic pressure feedback for 1-dof hydraulic driven mechanical system

The linearised version from valve input to actuator position consists of a lightly damped second order system in series with an integrator. When controlled with proportional position feedback, only low performance can be obtained. In order to achieve higher bandwidth, the resonance of second order system has to be damped sufficiently. This can be done by pressure feedback [16]. But the inner loop with pressure difference feedback will decrease the rigidity of the system. To solve this problem, an alternative method can be applied using dynamic pressure feedback, in which pressure difference feedback signals are filtered by a one-order high pass band filter. The dynamic pressure feedback correction is equivalent to acceleration feedback without changing the undamped eigenfrequency ω_{hi} [16]. In this manner a closed loop bandwidth approximately equal to ω_{hi} can be attained.

Defining ξ_h as the original damping ratio and ξ_h'' is the desired damping ratio, and then the dynamic pressure feedback gain k_{dp} can be calculated by

$$k_{dp}=\frac{2(\xi_h''-\xi_h)\cdot\sigma_i {A_p}^2}{k_{a,i}k_q\omega_{hi}} \quad (2)$$

The cutting frequency of the high pass filter is assigned with $\omega_{hi}/3$. A compromise of the damping ratio has to be achieved, because the damping ratio with higher value will also decrease the close loop bandwidth.

4. Modal Space Decoupled controller (MSDC)

The structure of a modal space controller is similar to the conventional joint space control, however, the signals including control errors, control outputs and pressure difference feedbacks are transformed into decoupled modal space by the unitary decoupling matrix, **U**, and so the coupling effects between all the actuators are fully considered and compensated. The proportional gains and dynamic pressure feedback functions are also tuned in modal space. The unitary decoupling matrix, **U**, will be chosen from the simplified linearised version at neutral position to the more complicated pose dependent one. The criterion of choosing is to ensure both good performance and facilitating the real time implementation. In steady state, the term of gravity compensation added at the controller output is written as $\frac{k_{ce}}{k_q A_p^2}\mathbf{J}_{lx}^{\mathrm{T}-1}\mathbf{G}$, the steady errors caused by gravity can be reduced to almost zero. So the control inputs of the servo valves can be expressed as

$$\begin{aligned}\bar{\mathbf{i}}_u &= \mathbf{U}\,\mathrm{diag}(\begin{bmatrix}k_{a,1} & k_{a,2} & \cdots & k_{a,6}\end{bmatrix}^{\mathrm{T}})\mathbf{U}^{\mathrm{T}}\mathbf{e}\\ &\cdots+\mathbf{U}\,\mathrm{diag}\left(\begin{bmatrix}k_{dp,1}\dfrac{\tau_{c,1}s}{\tau_{c,1}s+1} & k_{dp,2}\dfrac{\tau_{c,2}s}{\tau_{c,2}s+1} & \cdots & k_{dp,6}\dfrac{\tau_{c,6}s}{\tau_{c,6}s+1}\end{bmatrix}^{\mathrm{T}}\right)\mathbf{U}^{\mathrm{T}}\mathbf{P}_L \quad (17)\\ &\cdots+\frac{k_{ce}}{k_q A_p^2}\mathbf{J}_{lx}^{\mathrm{T}-1}\mathbf{G}\end{aligned}$$

Where, $\mathbf{e}=\bar{\mathbf{l}}_{com}-\bar{\mathbf{l}}$ is the position error, $\bar{\mathbf{l}}_{com}$ is the actuator length command in terms of inverse kinematics. For the ease of programming, each element of $\bar{\mathbf{i}}_u$ is given here as

$$\bar{i}_{u,i}=\sum_{j=1}^{6}\left(\left(\sum_{k=1}^{6}U_{ik}U_{jk}k_{a,k}\right)e_j+\left(\sum_{k=1}^{6}U_{ik}U_{jk}k_{dp,k}\frac{\tau_{c,k}s}{\tau_{c,k}s+1}\right)P_{Lj}+\frac{k_{ce}}{k_q A_p^2}J_{ij}G_j\right) \quad (18)$$

Where, $\mathbf{e}=(e_j),\mathbf{U}=(U_{jk}),\mathbf{P}_L=(P_{Lj}),\mathbf{J}_{lx}^{\mathrm{T}-1}=(J_{ij}),\mathbf{G}=(G_j)$ with $i,j,k=1,2\cdots6$.

Analyzing Eqs.(17,18), when $k_{a,1}=k_{a,2}=\cdots=k_{a,6}$ and $k_{dp,1}=k_{dp,2}=\cdots=k_{dp,6}$, the modal space controller degenerates into the conventional counterpart

5. Results and Discussions

The trajectory performance of the proposed controller and the conventional joint space controller was presented. It evaluates the performance with respect to how feasible the controllers will follow a trajectory. Feasible means that once being on the reference trajectory it is possible to stay on that trajectory. The complex multi-input, multi output (MIMO) system have been decoupled to six independent Single Input, Single Output (SISO) system and the control specifications was determined for each DOF independent of the others. A series of numerical simulations were carried out to test the effectiveness of the system, and the results verify the favorable tracking ability.

In the simulation procedure, the desired trajectories of the hydraulically driven 6 DOF Parallel Mechanism were the input commands of the controller, while, the controller provides the current applied to the hydraulic system. The sample time is set to 1ms. Comparing the effectiveness of the modal space decoupling controller with the conventional PID joint space, phase retarding and amplitude fading were chosen to evaluate how well the modal space decoupling controller can faithfully follow a trajectory.

The responses of sinusoidal inputs along six directions surge, sway, heave, roll, pitch, and yaw are given. The ability of the controller to follow the desired trajectory is clearly depicted in figure 3 to 6. The result indicates that the modal space decoupling controller has better tracking performance when compared to conventional PID controller. For the conventional joint space controller (CJS), the phase retarding for the linear in angular motions attains maximum value at 40.90º and 23.98º respectively. The modal space decoupling controller attains maximum phase retarding at 22.84º in linear motions and 0.975º in angular motions. The amplitude of the conventional PID controller fades at 0.54dB in linear motions and 0.47dB in angular motions. While for the modal space decoupling controller, the amplitude fades at 0.1696dB in linear motions and 0.082dB in angular motions.

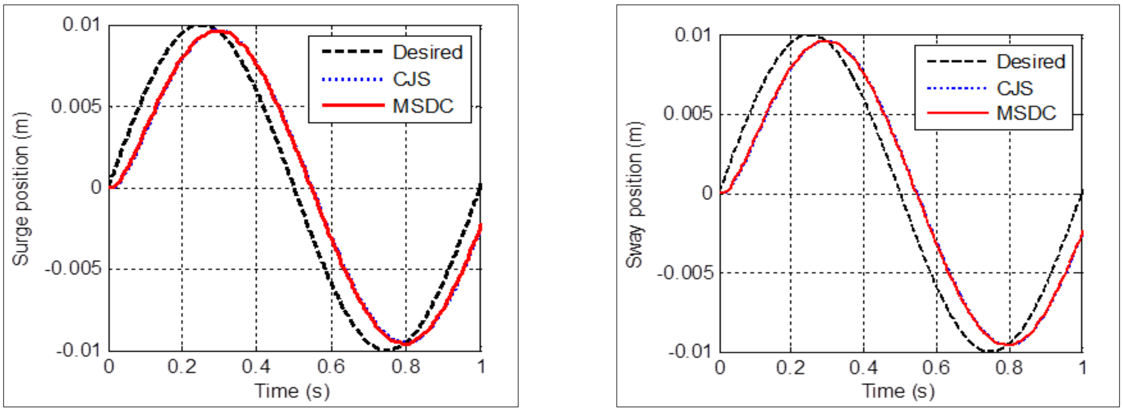

Figure 3 Simulation result of trajectory tracking performance

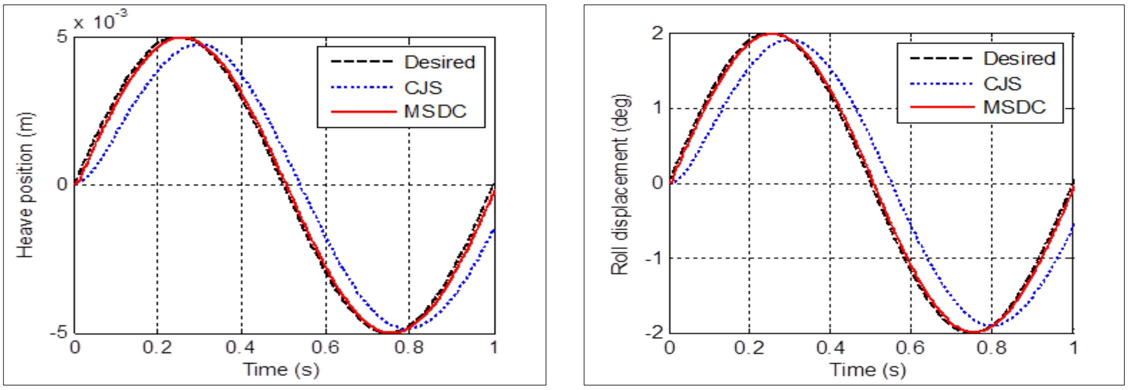

Figure 4 Simulation result of trajectory tracking performance

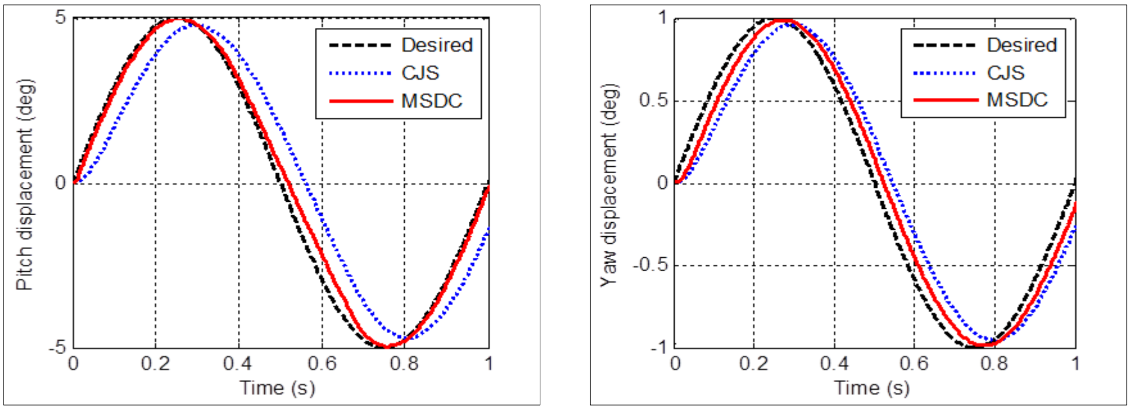

Figure 5 Simulation result of trajectory tracking performance

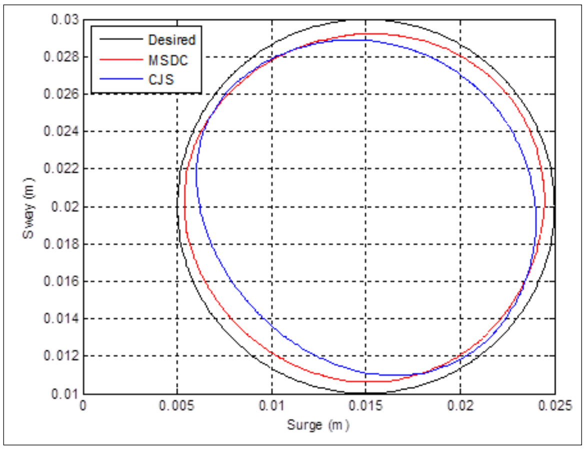

Figure 6 Simulation result of trajectory tracking performance

The evaluation of the control performance of the proposed control with the conventional joint space controller was further carried out by subjecting the two controllers to the tracking of a desired circular combined motion of surge and sway. This case is designed to test how a trajectory can be predefined from a combined surge and sway motion and how well the modal space decoupling control strategy performs in the context of tracking a combined circular motion. The system responses to the desired combined motions were shown in figure 7. From the simulation results the performance of the modal space decoupling control strategy is satisfactory and convincing. The predefined circular trajectory was well tracked much more by the proposed MSDC than the CJS.

6. Conclusion

The performance evaluation of the modal space decoupling controller was presented and discussed. The evaluation was with a view to examine the note how the modal space decoupling control and conventional control will follow a trajectory. The simulation result indicates that the modal space decoupling controller performed better and tracked a sinusoidal effectively when compared with conventional joint space controller. From the above result, it can be inferred that the proposed controller outperformed the conventional joint space controller through a remarkable tracking performance. This attribute exhibits the potential of the proposed controller for an effective and improved performance.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest.

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