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Self-tuning fuzzy PD-based stiffness controller of a 3×3 Stewart platform as a man-machine interface

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Abstract

Stewart Platform (SP) mechanism has wide application area on aerospace and manufacturing industry with its nonlinear structure allowing spatial motion capabilities. However, nonlinearities in the structure of the mechanism lead to complications in the dynamics of the system and result in complex control algorithms for dexterity in motion and force/torque feedback. Therefore, this paper aims to represent stiffness control by means of independent joint fuzzy-PD control algorithm with gain scheduling on an experimental 3×3 *SP parallel robotic mechanism to be used as a fly-by-wire flight control unit. Model and real system responses are compared employing stiffness control so that the model is valid for control design trials. Following the selection of optimum control coefficients of self-tuning structure, responses are compared with alternative control algorithms like fuzzy-PD, self-tuning fuzzy PD and PD controllers. Optimum control coefficients are selected minimizing force error integral over a spiral force path on nine chosen points on the workspace. However, torque feedback is applied minimizing the torque error for simple angular motions. System responses for selected controllers are presented and discussed.*

Key Words: *Stewart platform, stifness control, fuzzy control, gain scheduling*

1. Introduction

Stewart-Gough Platform related researches have gradually increased since it was first used as a flight simulator in 1965 by D. Stewart, connecting a stationary lower and a mobile upper platforms to the two ends of six actuators in parallel and obtaining three translational and three rotational Degrees of Freedom (DOF) in space [1]. Since the mechanism has a nonlinear kinematic-dynamic structure as a result of actuators in parallel, position/force control of the mobile platform is a real challenge [2]. Forward/inverse kinematic analysis of the parallel mechanism [3], dynamic behavior [4], control [5], design of different simulators [6], and manufacturing [3], are the topics that have been extensively studied. Among these, kinematic analysis research on SP resulting simpler mathematical solutions to reduce computation time is very significant.

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Dynamics of SP mechanisms is also very important area since it establishes the connection between input force/torque and output positional motion data. Both Newton-Euler [7], and Lagrange Methods [8], are employed for forward, inverse dynamics solutions by several researchers. Additionally, the Bond-Graph Method is employed for dynamic modeling of SP mechanism utilizing energy bonds between elements [9]. Workspace and singularity analysis is another research area of these mechanisms and since forward kinematics of parallel mechanisms are problematic, various solutions have been proposed [10].

Since SP mechanism was first employed as a position controlled simulator, limited number of force feedback applications exist in the field of haptic applications and of surgical simulators [11]. Consequently, force feedback parallel mechanisms have been studied in recent years, especially in the field of amniocentesis simulation [12], and in simulation of endoscopic surgeries in which impedance control is applied [13]. Additionally, haptic based parallel mechanisms are studied in hybrid vibration isolation [14], teleoperation [15], and for general applications [16], [17]. Hybrid vibration isolation study seeks the effect of force constant, multiplied by the force readings from six force sensors, on the isolation bandwidth. On the other hand, bilateral force feedback is employed between the master and slave on teleoperation management application in which variable force control coefficient as a function of the force, affecting the slave, is used.

Since SP mechanism is a nonlinear system, self-tuning fuzzy-PID based stiffness control would be an appropriate choice for force feedback control. Variety of successful control applications are based on gain scheduling method [18], for which direct application on parallel mechanisms and especially on SP mechanism is not present. However, fuzzy gain scheduling itself is used in a few number of researches [19].

In this research, self tuning fuzzy PD control of a 3×3 SP actuated by linear DC motors as a man-machine interface is aimed which is intended to manipulate Spatially Moving Vehicles (SMV) allowing force feedback capability. Through the paper, first, suitability of the SP mechanism to manipulate SMVs is discussed. Then, real system and the simulation environment are presented and their responses are compared for initial control design studies. Introducing the intended control algorithm, application to simulation system and results are discussed. Besides PD and self-tuning fuzzy PD control connected in parallel (STFPD+PD); PD, fuzzy PD (FPD) and self-tuning fuzzy PD control (STFPD) are experimented for comparison purposes between controllers. Lastly, the possible future work of the subject is mentioned.

2. SP flight control unit

2.1. SP mechanism

Many applications related to physical simulation of spatial motion have been performed since the first emergence of SP mechanisms. The SP is a parallel robotic mechanism which is mostly used for simulating flight patterns of flying objects and is also employed in manufacturing industry where spatial motion is needed for complex surface machining. It has a moving upper plate and a stationary lower plate and six parallel-connected actuator legs attached to these plates which enable the upper plate for spatial motion. In present study, 3×3 SP is used in which six legs are connected to upper platform at three points and are connected to the lower stationary platform at three points as well. Since the moving plate of the mechanism is capable of spatial motion, this system can be used to manipulate vehicles in space like a six degree of freedom joystick.

2.2. Spatial motion manipulation by an SP

Pilots are generally forced to interact with more than one joystick in order to manage the navigation of an SMV. For instance, a lever, a pedal and a collective arm is employed to control a helicopter. The collective arm provides ascending and descending motion of a helicopter in z, vertical direction. There exists a gas arm on top of the collective in order to provide instantaneous power to the vehicle. Pedals are used for yaw motion around z axis and the lever is for pitch and roll motion of a helicopter. A standard 3×3 SP mechanism with force feedback, apparently, allows the user to manipulate any SMVs from a single location. The user employs the lever on the SP to move the vehicle. The motion of the SP is interpreted by an interface in order to obtain desired positional/directional motions for the vehicle.

3. Experimental setup

As seen on Figure 1-a, the system consists of a lever (A), a six axis force/torque transducer (B), ATI nano25, a motion control card interface (C), NI UMI-7774, a six axis motion control card (D), NI PCI-7356, a PC, linear motor drivers of E210-VF (E), and a 3×3 SP. Lever is rigidly assembled to the force/torque transducer while the transducer is also rigidly assembled to the SP so that force/torque interaction between the lever and the SP is fully measurable.

The forces/torques which are applied to the lever by the user to manipulate the SMV are sensed by the force/torque transducer, (three axis of force and three axis of torque) and converted to the analogue voltage data (± 10 volts) separately for each axis. The motion control card's ADC converts the analogue data to sixteen bits of digital data. The software that is written for this system receives the digital data and converts it to numerical values of forces and torques. By this way, the software interprets the pilot's control commands (or more understandably, in which direction in space s/he intends moving/rotating to) and calculates the values for the motion control card to produce the analogue voltage output. The software uses inverse kinematics to calculate the legs' lengths. Since linear DC actuator drivers are running under force/torque mode, the ± 10 Volts of signals is sent to linear motors' drivers to convert the data to actuating forces by controlling the motors' current in which full control capability is transferred to the designer comparing to velocity mode where internal velocity control algorithms of the drivers are heavily used. The encoder data of selectable resolutions (1mm to 1 μm) from the auxiliary encoder output of the driver is used for positional feedback purposes. By

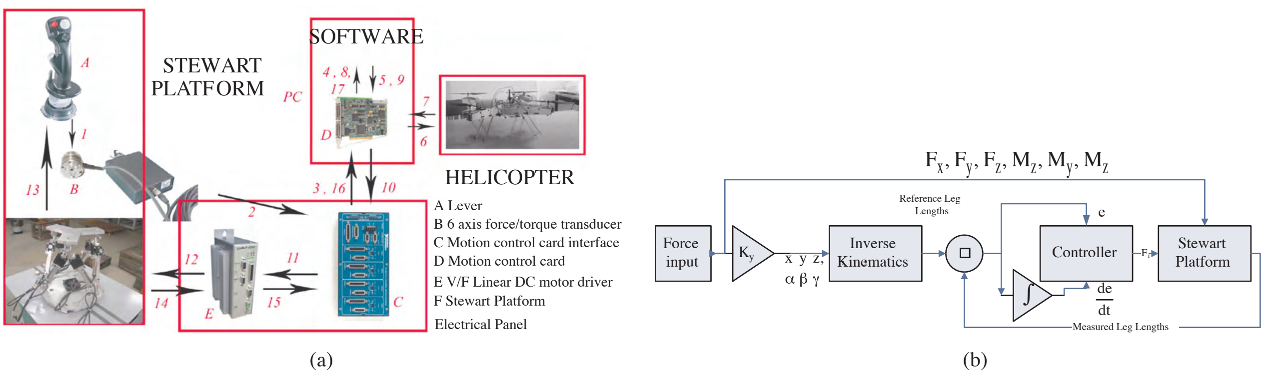
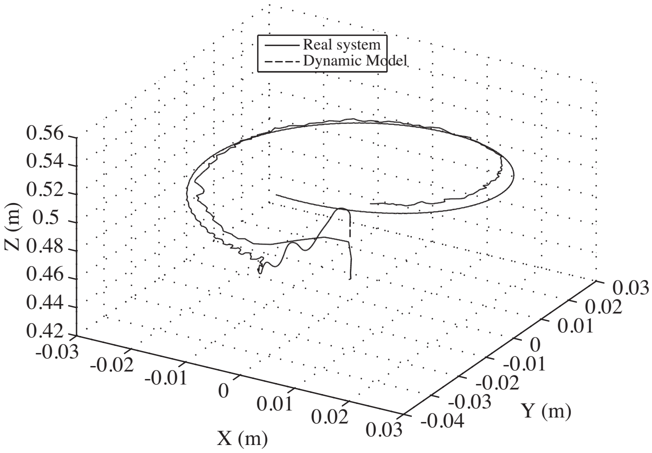
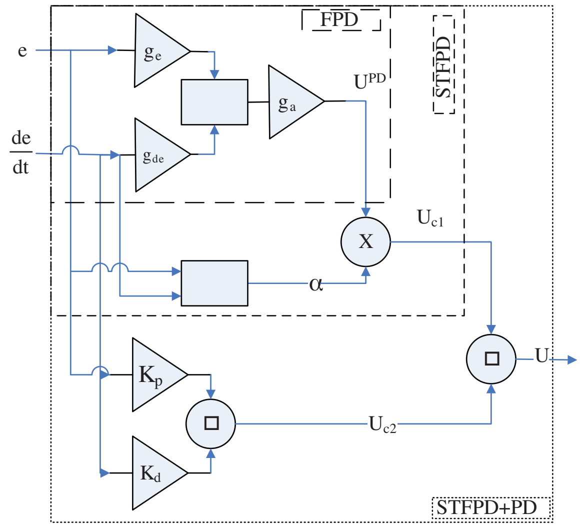


Figure 1. a) General components of the overall SP mechatronic system. b) Stiffness control block diagram containing experimental/simulation system, controller and inverse kinematics.



(a)



(a)

Figure 2. a) Comparison of simulation and real system responses. b) Block diagram of the control algorithms.

these complicated control mechanisms, the pilot feels the external forces through the lever which is acting on the vehicle.

A Simulink - Sim-mechanics model of the 3×3 SP mechanism is constructed to initially test the proposed controllers, Figure 2-a. System parameters can be provided as, mobile platform mass (M_u): 1,387 kg, motor shaft mass (m_u): 0,135 kg, motor body mass (m_d): 0,44 kg, mobile platform connection points' radius (r_p): 0,15 m, stationary platform connection points' radius (r_b): 0,175 m, damping coeff. of joints (c_f): 0,03 Nm.s/deg., virtual spring coeff. (K_y): 140 N/m, motors inductances (L_a): 1,5 mH, motor resistances (R_a): 10 ohm, motor force coeff. (K_t): 11 N/A. A stiffness control algorithm is applied to both simulation and real system in which a virtual spring is assumed to be present between the user and the lever so that when a spatial force/torque is applied to the platform by the user, it is converted to a displacement, Figure 1-b. Then, the problem becomes a position control from this moment, yet, the selection of virtual spring constant is somewhat important for the system performance which interacts with the user's variable hand stiffness. In our problem, virtual spring constant is chosen as not to sacrifice system performance [20]. For the exact force/torque application to the real system and to the simulation environment, system response seems to be matching in good degree, Figure 2-a, which can be interpreted as a satisfactory dynamic model to be used as an initial control design studies. The present difference between two responses is caused by the compensation algorithm of the motion control card itself.

4. Fuzzy logic based stiffness control and simulation results

Since SP mechanism has nonlinear dynamic characteristics, it would be meaningless to expect a constant control performance throughout its workspace. The term "Transparency" is used in haptic applications to describe the reflected force/torque quality to the user of a force feedback device in which there exists an "intended force/torque" to be reflected and "the force/torque that user feels". The difference between these two defines the transparency of any haptic device [21], and it is caused by several factors some of which are mechanical limitations, like, backlash, and control algorithm for force feedback. In this study, free space simulation is aimed in which no force/torque should be felt by the user when moving the lever on SP.

4.1. FPD controller

To avoid the oscillatory effect of integral action on system dynamics, fuzzy-supported PD controller is the base for the controller trials, Figure 2-b. Rule base is constructed as described in [18]. PD control is described as,

$$U^{PD} = k_P \cdot e + k_d \cdot \dot{e} \tag{1}$$

Selecting e and $\dot{e}$ as fuzzy variables, Eqn. (1) describes the controller. Relation between the coefficients of FPD and PD controllers based on Figure 2-b and the controller output can be written as,

$$k_P = g_a \cdot F\{g_e\}, k_D = g_a \cdot F\{g_{de}\} \Rightarrow U^{PD} = g_a \cdot [F\{g_e\} \cdot e + F\{g_{de}\} \cdot \dot{e}] \tag{2}$$

4.2. STFPD controller

FPD controller may adjust its derivative effect in real time, by placing a parallel STF rule base which adjust the g_a parameter as in Figure 2-b. This self-tuning effect can be represented as,

$$U_{c1} = U^{PD} \cdot \underbrace{F\{e, \dot{e}\}}_{\alpha} \tag{3}$$

U^{PD} is FPD output which is provided in Eqn. (1) and is multiplied by a parallel rule base shown in Table 1, which is dependent on e and $\dot{e}$ where VB is very big, MB is medium big, B is big, Z is zero, S is small, MS is medium small, and VS is very small.

4.3. STFPD + PD controller

In order to obtain better controller performance, a classic PD controller is placed parallel to the STFPD controller in which rule bases used are same as in Table 1 [19]. Controller output can be written as,

$$U = K_P \cdot e + K_D \cdot \dot{e} + U^{PD} \cdot F\{e, \dot{e}\} \tag{4}$$

Table 1 lists the fuzzy rule base, where NB is negative big, NM is negative medium, NS is negative small, Z is zero, PS is positive small, PM is positive medium and PB is positive big.

Table 1. Rule base for Fuzzy PD controller and Rule base for Self Tuning part

Δe/e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PS	PM	PB	PB	PB

Δe/e	NB	NM	NS	Z	PS	PM	PB
NB	VB	VB	VB	B	SB	S	Z
NM	VB	VB	B	B	MB	S	VS
NS	VB	MB	B	VB	VS	S	VS
Z	S	SB	MB	Z	MB	SB	S
PS	VS	S	VS	VB	B	MB	VB
PM	VS	S	MB	B	B	VB	VB
PB	Z	S	SB	B	VB	VB	VB

4.4. Force/Torque responses of SP for fuzzy PD based stiffness control

Because of the nonlinear dynamics and the resultant varying control performances throughout the workspace, certain locations for control performance evaluation are selected in the workspace illustrated in Figure 3-b. Since the SP mechanism used is symmetric about x axis, 9 points of the workspace are selected on one side of x-axis and system is forced to follow a spiral force path started from these points. Figure 3-a shows effects of the variation of controller coefficients on force error integrals. Force error integral is kept to be small for best performance along this spiral path. Selected points are extreme locations on z and x axis (4), an extreme

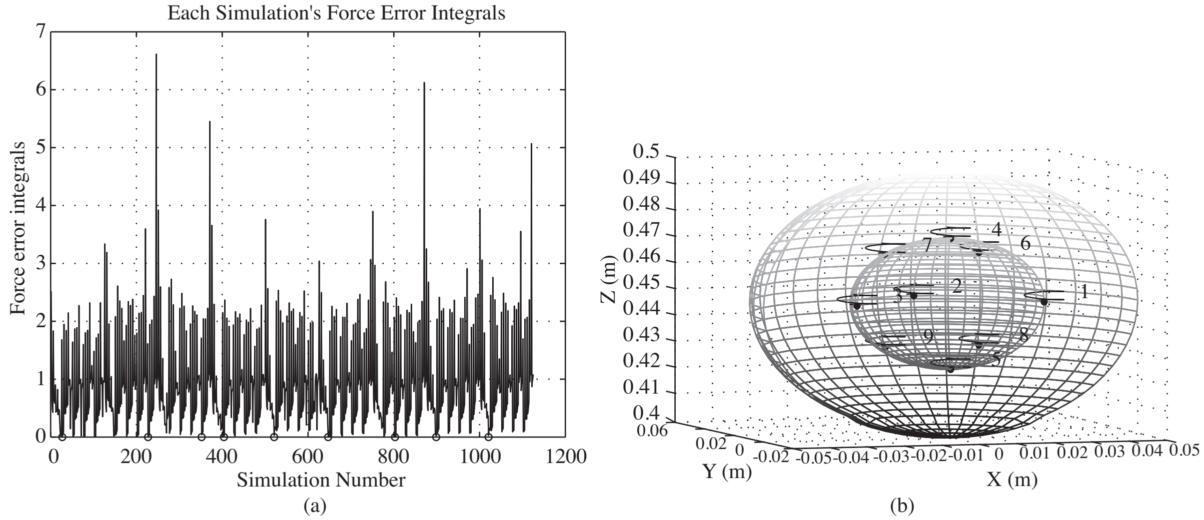


Figure 3. a) Effects of Controller coefficient combinations on 9 test points on workspace. b) Selected point locations on half of the spherical workspace and spiral force path for controller trials.

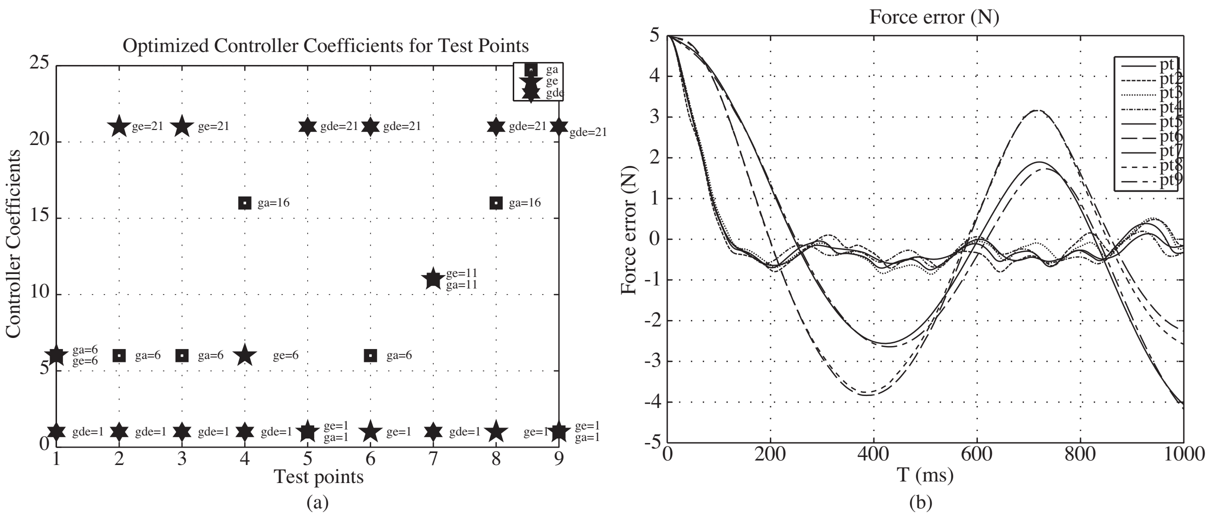
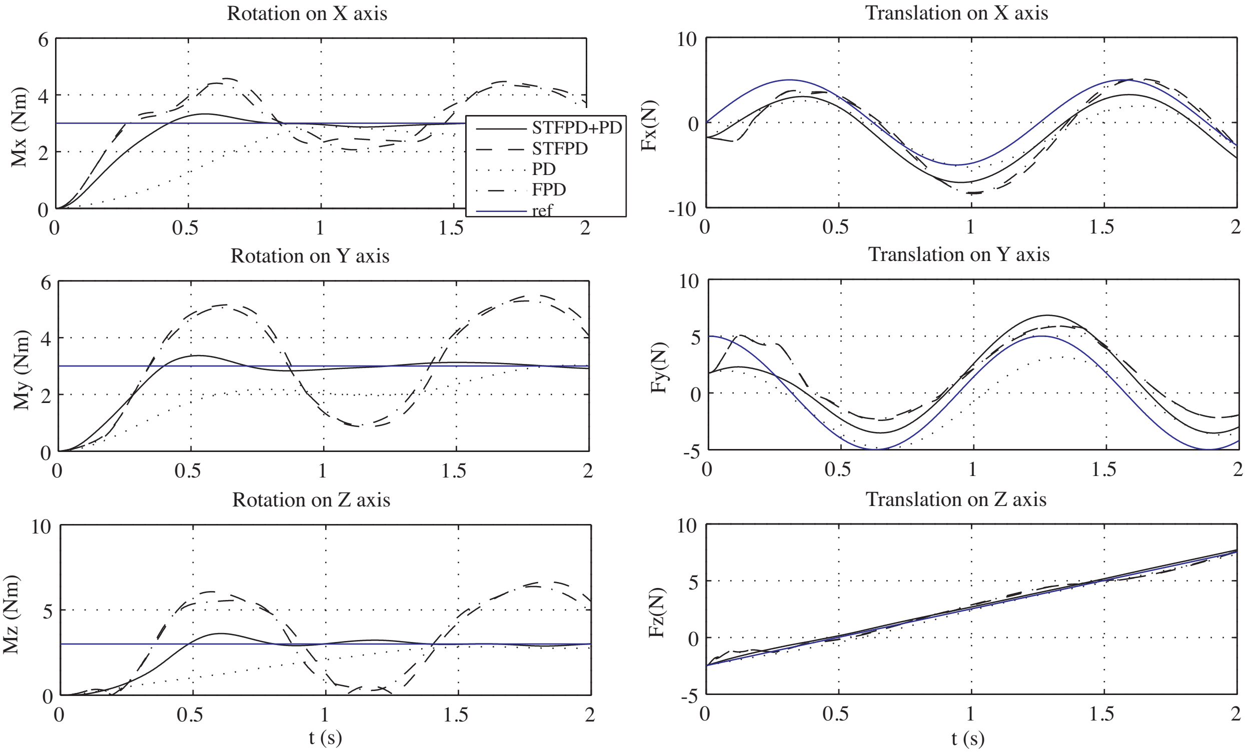


Figure 4. a) Optimum controller coefficients at test points based on force integral error over spiral force path. b) Force errors on test points.



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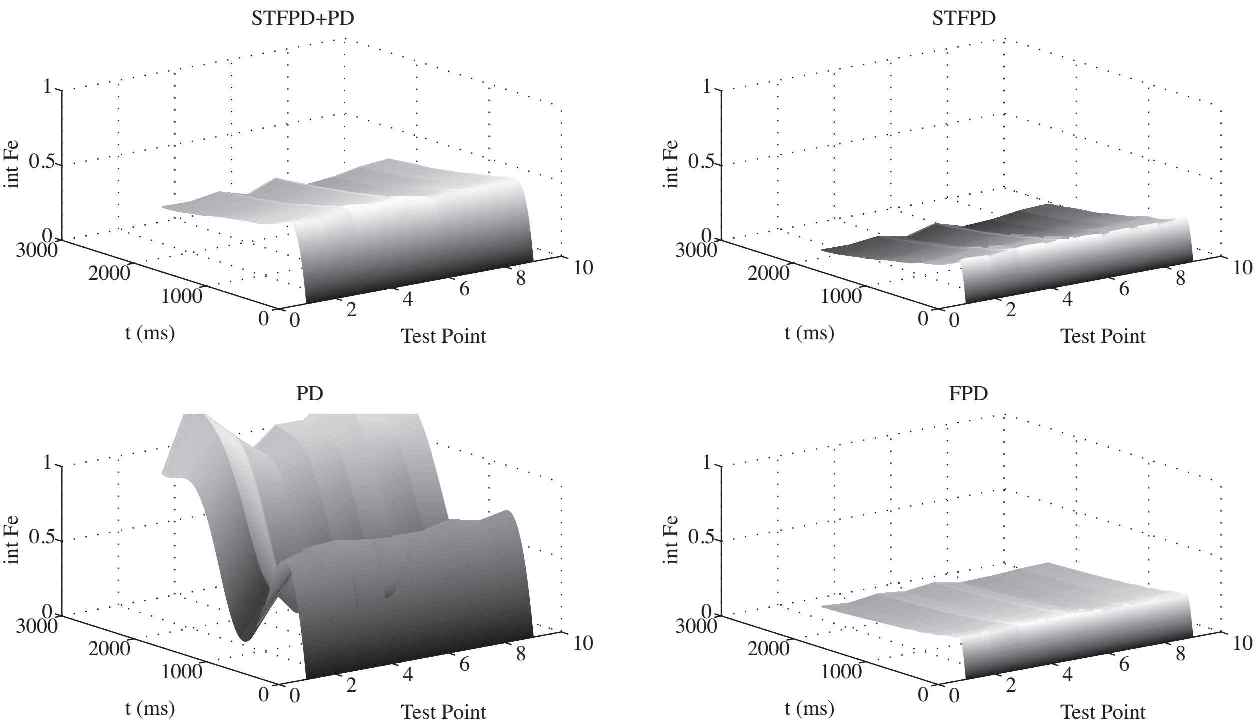

(b)

Figure 5. a) Answers of Controllers on a randomly selected point in workspace. b) Integral of force error at test points for selected controllers.

location on y axis and 4 extreme locations for which their angle to the origin is 45 degrees. On 1^{st}, 2^{nd}, 3^{rd}, 4^{th} and 7^{th} test points, g_a=9, g_e=13, g_{de}=1 controller gain values are used, Figure 4-a. On the other 5th, 6th, 8th and 9th points, the force error is growing as shown in Figure 4-b. Because of this reason, corresponding coefficients of these points are neglected finding the range of controller parameters. Since three of the controllers for trial are fuzzy-based, optimum controller coefficients should be searched for best performance and self-tuning should be performed around these optimum control coefficients shown in Figure 4-a.

Figure 5-b illustrates the force error integral values for selected controllers. STFPD controller performance seems to be the best comparing to PD controller, where system responses are unstable, and to STFPD + PD controller where magnitude of error is high despite the fact that the responses are satisfactory. Figure 6 shows the torque error integrals against 3 Nm torque input around three axis over the test points for selected controllers. Controllers are applied to a randomly selected point on workspace with constant 3 Nm input torque and a spiral force input on each axis as in Figure 5-a. STFPD + PD and PD controllers are satisfactory although PD controller response is comparably late. Additionally, FPD and STFPD controllers have oscillatory response which is not acceptable.

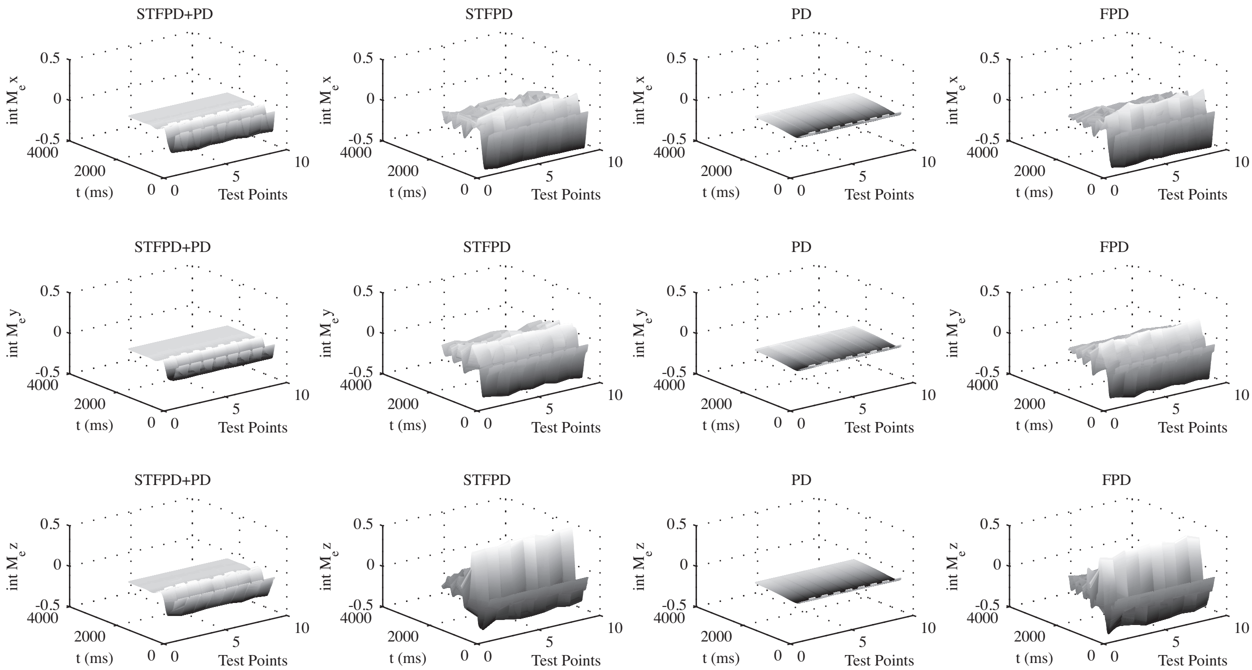

Figure 6. Integral of torque error at test points for selected controllers.

5. Conclusion

In this study, a diverse use of SP mechanism is introduced in which the potential of spatial motion simulation of the intended mechanism is reflected to the manipulation of SMVs. Though versatile use of SP mechanism is present from manufacturing to spatial motion simulation, manipulating vehicles in space by this mechanism with force feedback has been left untouched. Since the platform is utilized as a spatial joystick with some certain weight and internal damping of the bearings, the moving platform is to be stationed on a mid-point when not used or in auto-pilot. Then, moving the upper platform should not require any extra effort for the user, called "assisted-user mode". Thus, a stiffness control as a free space simulator is proposed with an STFPD controller and the results of the response of the system as a means of the reflected force to the user's hand is provided in simulation environment. Several steps need to be taken in order to finalize this research, some of which are, kinematically, to determine the workspace requirements of real cockpit controllers for various SMVs, to investigate different force control algorithms for better force transparency and to search for an optimized mechanical and mechatronic design approach to reach a more feasible solutions that fits into the intended vehicle.

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