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Simulation of the Admittance Control Based Haptic Interface Device

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Abstract

The purpose of this paper is to demonstrate the simulation of the haptic interface device utilizing the admittance control method for the applications of human/virtual environment interaction. . The dynamics of the haptic interface is derived, and then it is integrated with the admittance interaction loop. In doing so, firstly, the haptic device is simulated and the design of it is done through Adams software. Further, the control loop is simulated in MATLAB/Simulink and the link angles in Adams are imported into MATLAB. For the purpose of simulation, an environment is simulated interacting with the haptic device and eventually, a collision is occurred in the simulated environment. Moreover, a desired position to generate the collision effect iscalculated and is controlled during the simulation process. Then, the required torque command for this position is computed and is given to the motors of simulated haptic interface. There should be a real-time relationship between the haptic control loop and the simulated haptic interface. In this work, thefeedback linearization method is utilized for the control loop. For the purpose of verification, the model of the haptic interface device of the Mechatronics and Robotics Laboratory is used in simulation.

Keywords:*Haptic Interface; Impedance Control; Admittance Control; Real-Time.*

1. Introduction

A haptic interface links a human operator with a virtual environment in such a way that the user feels the scene with the sense of touch. The first model of haptic interface was made in Northwestern University by Brown and Colgate in early of decade 90 that was the 1Dof device. Desktop haptic devices are already finding widespread use as force displays for computer games, nanoscale manipulation, and surgical simulators [5]. Haptic engineers typically employ three criteria when designing haptic mechanisms i. *Free space must feel free*, ii. *Solid virtual objects must feel stiff*, iii. *Virtual constraints must not be easily saturated* [6].

The controller of this type of systems has to emulate the interaction with the virtual objects, while maintaining transparency in unconstraint motion. [7]. Impedance control and admittance control are the most application of control methods forthe haptic devise. In the impedance control systems the motion commanded by the operator isdetected and the force that isgenerated by the haptic device becontrolled and in the admittance control methodsthe force commanded by the operator be measuredandthe velocity or displacement of the haptic device be controlled [1The dynamic equation of the haptic interface that is used in this work is nonlinear, and therefore, the best proposed control method for this device is feedback linereazation methodthat this method is be discussedin the following.

2. Model of the haptic interaction

Model of the haptic interaction considered in this workis given in Fig.1. thismodel is consists of two parts:a virtual environment and a haptic interface device. in the first part of the model, the force $F_h$that applied by human operator is used to generate a desired tool position for the haptic device, based upon the environmental model embodied by the damping , B, and stiffness, K,and position of tool. An inverse kinematics module that represented by the block J^{-1}, converts the tool position into a set of commanded joint angles for the Haptic device, $q_d$then a PD controller calculates the motor torques for the haptic device based to servo the actual angle that sensed by the encoder to the desired joint angle. Torque τ that is commanded for the haptic device is sum of controller torque, τ_{ac} and torque exerted by human operator τ_h .

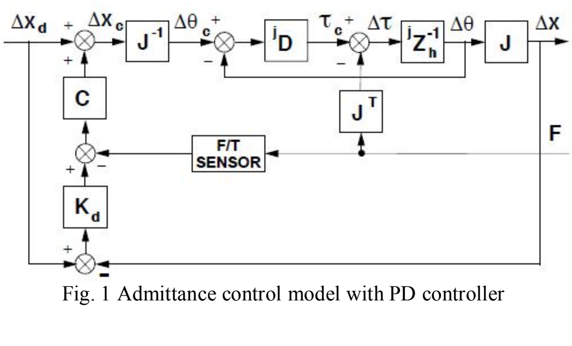

Fig. 1 Admittance control model with PD controller

The impedance is defined as the relationship between the velocity and the force. Therefore, the Closed- loop impedance represents therelationship between the input forces to the output position in the transfer function form:

$$Z_{hCL} = \frac{F}{X} \quad \textbf{(1)}$$

With the considering to the definition of closed-loop impedance and the block diagram in Fig.1, the following result is derived for closed-loop impedance:

$$\frac{F_h}{X} = \frac{Z_h(C+I)}{CZ_e^{-1}-1} \quad \textbf{(2)}$$

In the above relationship, if the gain of PD controller is sufficiently largecompared to the impedance of the haptic interface, then the closed-loop impedance that felt bythe user is:

$$\frac{F_h}{X} = \frac{1}{Z_e} \quad \textbf{(3)}$$

Therefore in this control method Z_{hCL} approaches the environment impedance Z_e.

3. Dynamic of the haptic interface

The haptic interface that is used in this work is a parallel drive mechanism. But this haptic interface can beanalyzedasasimplefour-link mechanism with the simplification that is done. For analyses of this device in the first step the Denavit-Hartenbergparameters of the mechanisms is derived (see Table 1).

Table 1Link parameters for haptic interface device

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	L_1	θ_1
2	-90	0.4	0.2	θ_2
3	0	580	340	θ_3
4	-90	0	L_3	θ_4
5	90	0	0	θ_5

Then with the substituting these parameters into:

$${}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{(4)}$$

The transformation matrices can be computed for each link. Then, the link transformation can be multiplied together to find the single transformation that relates frame 3 to base. The forward kinematics equation is the fourth column components of this single transformationmatrices, that is shown in the below.

$$\begin{aligned} x &= \ell_2 c_1 c_2 - \ell_3 s_{23} c_1 \\ y &= \ell_2 c_2 s_1 - \ell_3 s_{23} s_1 \\ z &= \ell_1 - \ell_2 s_2 - \ell_3 c_{23} \end{aligned} \quad \textbf{(5)}$$

Where $c_i = cos(\theta_i)$ and $s_i = sin(\theta_i)$ and L_i is length of links.
The Jacobean matrices should be computed byEq. (2)for exchanging of the Cartesian space velocities to joint space or convert the force ofhuman's operator to a torque,τ_h

$$J(\Theta) = \frac{\partial X}{\partial \Theta} \quad \textbf{(6)}$$

$$J = \begin{bmatrix} -\ell_2 s_1 c_2 + \ell_3 s_{23} s_1 & -\ell_2 c_1 s_2 - \ell_3 c_1 c_{23} & -\ell_3 c_1 c_{23} \\ \ell_2 c_1 c_2 - \ell_3 s_{23} c_1 & -\ell_2 s_1 s_2 - \ell_3 s_1 c_{23} & -\ell_3 s_1 c_{23} \\ 0 & -\ell_2 c_2 + \ell_3 s_{23} & \ell_3 s_{23} \end{bmatrix} \quad \textbf{(7)}$$

Due to the fact that he feedback linearization method is used in this work, Therefore the dynamic equation of the haptic interface device should be derived. This equation is evaluated with the iterative Newton-Euler dynamic algorithm. soin the first step, link velocities and acceleration are iteratively computed from link 1 out to link 3 and Newton-Euler equation are applied to each link. And in the Second step, forces and torques of interaction and joint actuator torques are computed recursively from link 3 back to link 1 then evaluated these equations in the matrix form

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \quad \textbf{(8)}$$

Where $M(q)$ is the 3×3 mass matrix of the manipulator $C(q,\dot{q})$ is a 3×1 vector of centrifugal and Coriolis terms, and $G(q)$ is a 3×1 vector of gravity terms.

4. Feedback linearization method

The dynamic equation of the haptic interface that is used in this work is nonlinear, and therefore, the best proposed control method for this device is feedback linereazation method.In this control method as regards that the dynamic equation of an n-link rigid robot in matrix form

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = u \quad \textbf{(9)}$$

The idea of inverse dynamics is to seek a nonlinear feedback control law

$$u = f(q,\dot{q},t) \quad \textbf{(10)}$$

Which, when substituted into Eq .9, results in a linear closed-loop system. For general nonlinear systems, such a control law may be quite difficult or impossible to find. In the case of the manipulator dynamics given by Eq .9 however, the problem is actually easy. By inspecting Eq .9, we see that if we choose the control *u* according to the equation

$$u = M(q)a_q + C(q,\dot{q})\dot{q} + g(q) \qquad \textbf{(11)}$$

Then, since the inertia matrix *M* is invertible, the combined system given by Eq .(9)-(11) reduced to

$$\ddot{q} = a_q \qquad \textbf{(12)}$$

Eq. 12 is known as the double integrator system as it represents *n* uncoupled double integrators and the system given by this equation is linear and decoupled. Assuming that a_q is a function only of q_k and $\dot{q}_k$

$$a_q = \ddot{q}_d(t) - K_p\tilde{q} - K_d\dot{\tilde{q}} \qquad \textbf{(13)}$$

Where $\tilde{q} = q - q_d$, $\dot{\tilde{q}} = \dot{q} - \dot{q}_d$, K_p and K_d are diagonal matrices with diagonal elements consisting of position and velocity gain, respectively and the reference trajectory

$$t \rightarrow (q_d(t), \dot{q}_d(t), \ddot{q}_d(t)) \qquad \textbf{(14)}$$

Defines the desired of joint position, velocities, and accelerations then the closed-loop system will be decoupled.
Substituting Eq .13, intoEq .12, results in

$$\ddot{\tilde{q}}(t) + K_d\dot{\tilde{q}}(t) + K_p\tilde{q}(t) = 0 \qquad \textbf{(15)}$$

With choice for the gain matrices

$$K_p = \begin{bmatrix} w_1^2 & 0 & \dots & 0 \\ 0 & w_2^2 & \dots & 0 \\ \vdots & & \ddots & 0 \\ 0 & 0 & \dots & w_n^2 \end{bmatrix}, K_d = \begin{bmatrix} 2\xi w_1 & 0 & \dots & 0 \\ 0 & 2\xi w_2 & \dots & 0 \\ \vdots & & \ddots & 0 \\ 0 & 0 & \dots & 2\xi w_n \end{bmatrix} \qquad \textbf{(16)}$$

Where results in a decoupled closed-loop system with each joint response equal to the response of a second order system with control bandwidth in *rad/s*, ω_i anddamping ratio ξ that control bandwidth $\omega_i$determines the speed of response of the joint, or equivalently, the rate of decay of the tracking error and damping ratio ξ determines time response and performance of system.

5. Simulation of the haptic interface

For the purpose of verification, the model of the haptic interface device of the Mechatronics and Robotics Laboratory is used in simulationof haptic interface device. This haptic interface device has a six DOF, with three active DOF for detect of tools position, and three passive DOF for detect the orientation of virtual tool. In order to simulate the haptic interface device, in the first step should be design the parts of this device in the Solidworks software with the accurate dimension.In the second step, these parts are imported to the Adams software to assembling and simulate of links constrain. In this simulation the links angles and angular velocities are the outputof the Adams software and motors torque are the input. To this regards, the sensors and actuators are simulated in this simulation also. Final simulate model of this haptic interface is shown in Fig .2.

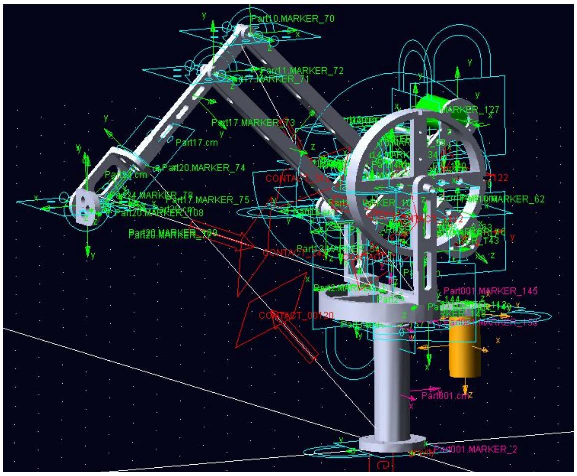

Fig.2 Simulation of haptic interface in Adams software with links constrain

In order to making real-time join the Adams software with the Simulink of MATLAB software, are used from control menu of Adams software. This menu creates an m-file in MATLB software that with the compiling of this file the real-time join is made.

6. Results and discussion

the stiffness, *K*, and damping, *B*, is used to simulate of virtual wall for determine the environment impedance in during of contacted with the virtual tool. and the goal of the haptic controller is to produce a closed-loop impedance at the gripper interface which matches the environmant impedance, Z_e . In this regards, the impedance error at the haptic interface is defined.The impedance error is different of the environment impedance withthe closed-loop impedance . so this different is more less , the closed-loop impedance is close to disired impedance .so in this section the impedance error is be discused with the different value of control gain an with the different value of the virtual stiffness and damping.
The impedance errors in three dimensions for different values of the stiffness, *K* and damping, *B* are shown in Figure Fig. 3 until Fig. 5.according to these figures, the error clearly decreases as the value of the stiffness and damping increases, on the other hand admittance control device is capable of simulating stiff environment.

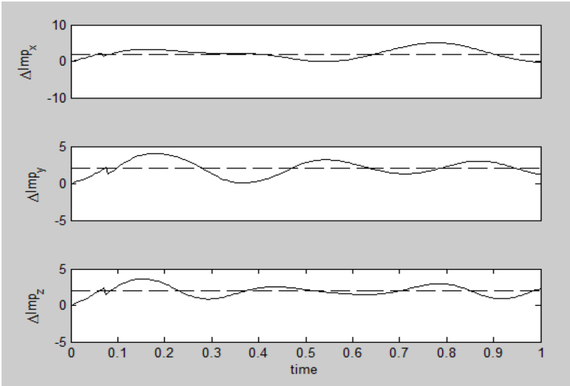

Fig. 3 Impedance error of Simulation results in three direction x, y and z by virtual stiffness *K=100N/m* and damping *B*=5*Nm/s* for virtual environment,and bandwidth *w=20* and damping ratio *ζ=1*for PD controller

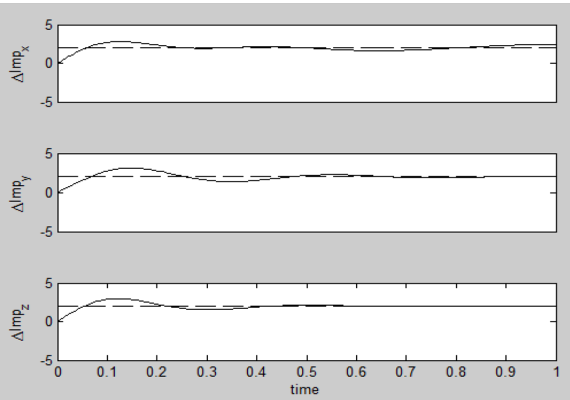

Fig. 4 Impedance error of Simulation results in three direction x, y and z by virtual stiffness *K=500N/m* and damping *B*=50*Nm/s* for virtual environment, and bandwidth *w=20* and damping ratio *ζ=1* for PD controller

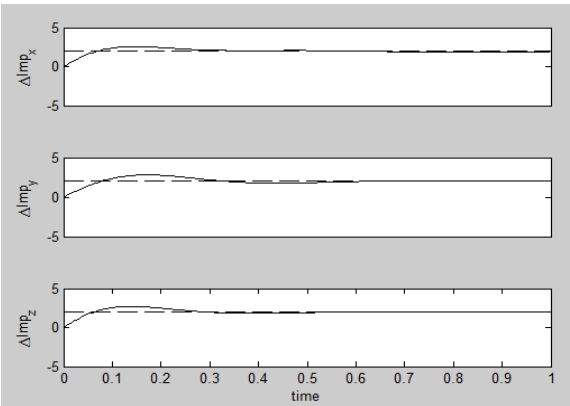

Fig. 5 Impedance error of Simulation results in three direction x, y and z by virtual stiffness *K=1000N/m* and damping *B*=300*Nm/s* for virtual environment, and bandwidth *w=20* and damping ratio *ζ=1* for PD controller

Comparison Fig.4 and Fig.6 are shown thatby an increase in bandwidth the error for the admittance controller is faster reduced. And comparison Fig.6 until Fig.8 are shown that by $\xi < 1$the response of system will be become to oscillating response and by $\xi = 1$ the response of system iscritically damped and by$\xi > 1$ the response is over damped. So in admittance control law, if the control gain is sufficiently large compared to the environment impedance, then the impedance felt by the user is approximately$Z_e$on the other hand the performance of the admittance controller improves rapidly with an increase in the control bandwidth of the joint servo loop.

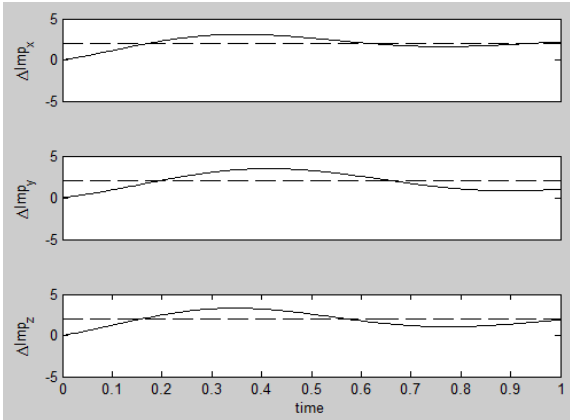

Fig. 6 Impedance error of Simulation results in three direction x, y and z by virtual stiffness *K=500N/m* and damping *B*=50*Nm/s* for virtual environment, and bandwidth *w=5*and damping ratio *ζ=1* for PD controller

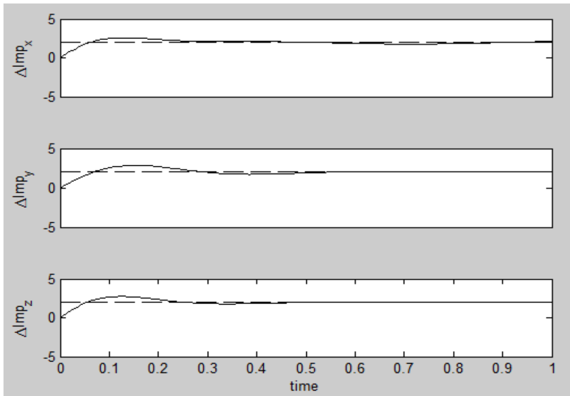

Fig. 7 Impedance error of Simulation results in three direction x, y and z by virtual stiffness *K=500N/m* and damping *B*=50*Nm/s* for virtual environment, and bandwidth *w=15*and damping ratio *ζ=1.5*for PD controller

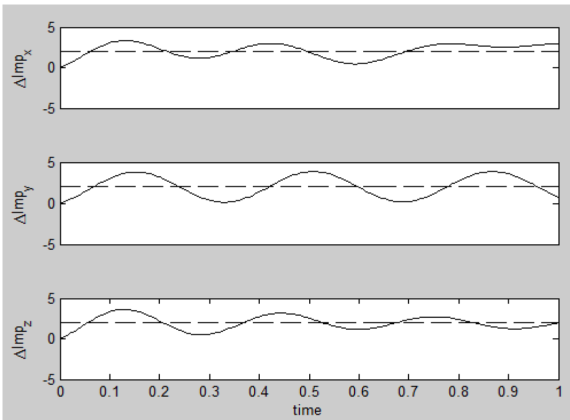

Fig. 8 Impedance error of Simulation results in three direction x, y and z by virtual stiffness *K=500N/m* and damping *B*=50*Nm/s* for virtual environment, and bandwidth *w=25*and damping ratio *ζ=0.5*for PD controller

7.Conclusions

This paper presented a brief description of the admittance control method in haptic system. Then, it was simulated in the MATLAB software and in the following, the haptic interface is simulated in the Adams software then it is integrated with the haptic interaction loop   Then the feedback linearization method and the effect of controller gains has been analyzed.

In this paper has been shown that, admittance control device is very suitable for stiff environment and it is suitable for nonlinear dynamics of device too.Also has been shown that, with increasing of control gainsthe impedance error is become smaller. And the impedance that felt by the user is close to the Z_e.

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