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# Teleoperation System with Force Feedback Joystick in Virtual Reality

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**Abstract:**
The key function of the teleoperation system is to support the operator to perform complex, uncertain tasks in hazardous and less structured environments, such as space, nuclear plants, battlefield, surveillance, and underwater operations. In this study a teleoperation system was designed by force feedback joystick, sliding mode non-linear controller and 2 degree of freedom revolute joint robot in Virtual Reality environment. Two inter-sectioned rigid walls were designed as an obstacle to simulate master/slave collision. The Virtual Reality Modeling Language (VRML) was used to display 3D objects with VRML viewer. Objects shape and appearance, motion, kinematic modeling and stiffness were designed. Simultaneous force and vision feedback helped operator to drive robot after collision, successfully. Sliding mode controller parameters K and $\Lambda$ achieved to optimal values by grid-search method which led to the best tracking performance; 4mm error in y axes and 1.5mm error in x axes, and 0.2 seconds settling time.

**Keywords:**
Joystick; Slotine Non-linear Controller; Teleoperation systems; Virtual Reality

## 1. INTRODUCTION

Teleoperation have been widely used in diversity of areas including applications from medical to satellite, entertainment to robot vision, and many others [1–4]. Teleoperation systems consist of operator, master, control system, slave and environment [5]. One of the main proposes of the robotics is multi task robots realization that can do complicated task connecting to environment. However with all of artificial intelligent effort, robots are not completely automated and cannot perform complicated missions without human aid. So robots need human supervision. This will lead to people rely on technology to be able to stay in their homes or do their complicated home tasks from their office. There are different types of Haptic devices, which one of the popular system used as master system in research projects is PHANTOM haptic device [6–8]. In this article a force feedback joystick was used. Joystick is one of the devices that can be used to control remote systems in teleoperation. Among available devices, such as joystick, mouse, switchbox, keyboard and touch-screen, the joystick is usually a better control device than others because the operators can identify better with the task. The joystick should be able to reflect forces that are experienced at the remote site [5].

Considering all of physical systems are nonlinear and classical control methods are linear, nonlinear control is one of the important and useful method that compose of two major method, feedback linearization and sliding control [9]. Various control methods already have been discussed for Teleoperation systems. Generally we divide these methods to the unilateral and bilateral control methods. Direct control of inverse dynamics, feedback error learning control and adaptive inverse dynamics trajectory control are some examples of unilateral controlling methods [6]. As some examples for bilateral control methods, we can mention direct force reflection, Position error based method, and three or four channels architecture [10]. Each method of what described above can be suitable and convenient for some specific cases and conditions. The aim of this thesis is controlling the exact position of robot by means of both force and visual feedbacks. In this article sliding mode nonlinear control is used to control robot position [9].

A robot with two degree of freedom and revolute joints has the role of slave in the system. Simulations were done on the collision of a virtual wall and cubic object, and then the challenge has been extended to robot and three-dimensional environment. Virtual Reality was used in order to display robot and environment. Virtual world includes dimensions, forces and collisions. In [8] researchers provided a control structure for teleoperation using contact force control and a virtual spring. They used active force control, which is needed for providing force feedback to a human operator. A virtual spring connects the master and slave systems and a closed-loop force controller compensates for the dynamics of the slave system, rendering transparent the effector of the slave robotic system. Space teleoperation under communication time delay which was studied in [2] made it possible to know conditions of a remote manipulator through force reflection. In order to overcome the difficulty of teleoperation system through delayed communication line, visual decorators were proposed in [11], which indicated some information superimposed on delayed video play out. To improve operability of teleoperation system, decorator can indicate future information over video play-out. Learn to Manipulating non rigid objects using haptic feedback and evaluating learning without haptic feedback were studied in [12]. In the current study, firstly teleoperation, master device robot and Virtual Reality were explained. Then a Slotine non-linear control was designed and applied. Finally results were illustrated.

## 2. METHODS

### 2.1 Teleoperation

A system operating over a distance from tens of centimeters (micro manipulation) to millions of kilometers (space applications) called Teleoperation, which components consist of operator, master, controller, slave and environment. **Figure 1** indicates the formal Teleoperation system. In automatically operated machines, controlling commands are transmitted mechanically or hydraulically to a teleoperator. The main requirements of teleoperation tasks contain force and torque feedback, stability in front of time delay and transparency. In this study, time delay is not considered, because the master joystick is connected to a same computer which slave robot is simulated in Virtual Reality.

To achieve the ideal response, the master slave force and position tracking was expressed by Equation 1 (see **Figure 2**). The equation physically corresponds to a massless, infinitely stick rod connecting the master and slave.

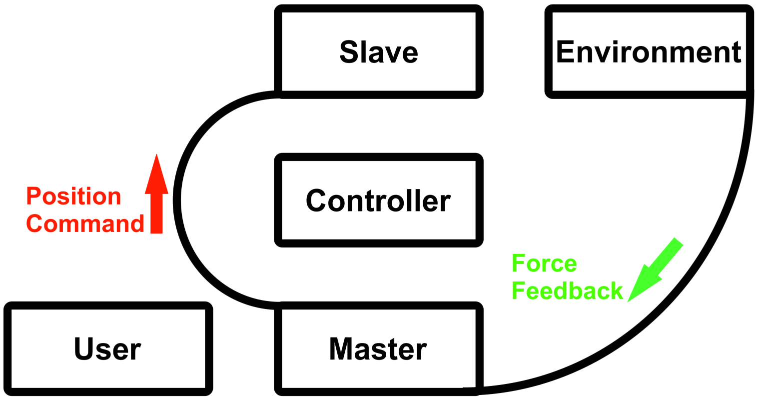

Figure 1. Teleoperation system. Typical components of teleoperation system are User, Master, Controller, Slave and Environment. User's position commands are transmitted by master to slave, while force feedback due to Slave-Environment collisions is retransmitted to the user

$$
\begin{aligned}
x_m(t) &= -x_s(t) \\
f_m(t) &= f_s(t)
\end{aligned}
\tag{1}
$$

Position control could be a proper method when a manipulator is following a trajectory through space, but when any contact is made between the end-effector and environment; mere position control might not suffice. If the stiffness of the end-effector, tool, or environment is high, it becomes increasingly difficult to perform operations due to manipulator presses against a surface.

## 2.2 Joystick: Device of Experiment

The model of joystick used in this research is Logitech Force-3D (Pro). The joystick consists of 12 programmable bottoms, high-accuracy revolute key, 8-way switch and 3 axes revolute stick in the input and two axes force feedback on the output. The joystick has "Spring Effect Strength" slider which controls the strength of the spring forces within a virtual contact. The joystick was used as a master device which it is a motorized and instrumented device that allows a human user to touch objects and manipulate as well within virtual reality background. The master mediates between the user and virtual environment making mechanical contact with the user and electrical connection with the virtual environment. At the virtual environment, force and motion are both simulated.

## 2.3 Robot Dynamics

At current article, simple 2 Degree of freedom (2-DOF) robot with revolute joints is chosen as slave system. Kinematic and Dynamic equations are derived [13], and are angles of robot links. M, C and G represent inertia Matrix, coriolis and centrifugal forces and effect of gravitational forces respectively. Moreover $\tau$ parameter represents joints torque. Note that all of the derivations are in time domain. After

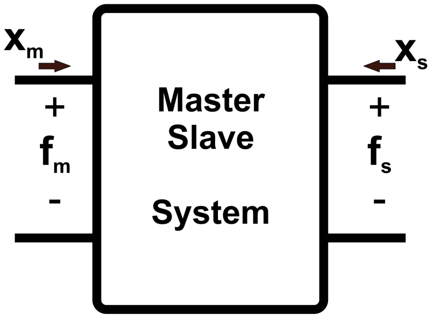

Figure 2. Master Slave System block diagram

all parameters of lagrangian dynamics were computed (Equation 2), then parameters are replaced by assuming numbers.

$$M(q)\ddot{q} + c(q,\dot{q})\dot{q} + g(q) = \tau \tag{2}$$

Both of robot links are 1kg with 0.5 meter length, Moment of inertia for both is 0.05 $\left(kg/m^2\right)$. Links have symmetric geometry. Eventually robot dynamic is:

$$\begin{bmatrix} 0.475+0.25\cos(q_2) & 0.1125+0.125\cos(q_2) \\ 0.1125+0.125\cos(q_2) & 0.1125 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} -0.125\sin(q_2)\dot{q}_2 & -0.125\sin(q_2)(\dot{q}_1+\dot{q}_2) \\ 0.125\sin(q_2)\dot{q}_1 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} 7.3575\cos(q_1)+2.4525\cos(q_1+q_2) \\ 2.4525\cos(q_1+q_2) \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \tag{3}$$

## 2.4 Virtual reality

Virtual Reality (VR) is a simulation in which computer graphics is used to create a realistic looking world. A key feature of VR is real time interactivity. Real time means that the computer is able to detect a user's input and modify the virtual world instantaneously. Modeling object shape, appearance, kinematic constraints, intelligent behavior and physical characteristics (weight, inertia, and hardness) are principal. The surface is monolithic (or static) and does not allow any relative motion of its component [14]. Virtual reality and animation software can be used for moving objects in 3D space with ability of object displaying. Simulation results can be monitored by Simulink 3D Animation. The software "Ligos V-Realm Builder 2.0", creates virtual environment, on the other hand Simulink 3D Animation toolbox inserts movement to the objects. V-Realm Builder software provides complete authoring, development and working environment for carrying out 3D visual simulations. The Virtual Reality Modeling Language (VRML) is the language has been used to display 3D objects with VRML viewer. The next step is to

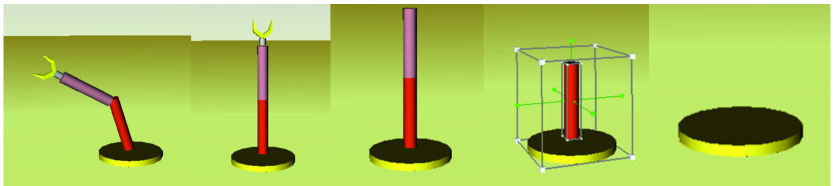

Figure 3. Steps of robot forming in VR

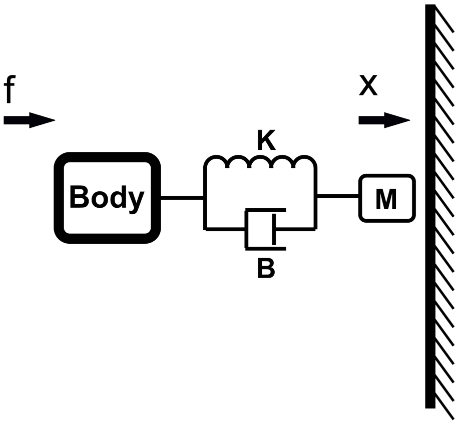

Figure 4. Collision modeling between wall and cube

model virtual world following kinematic modeling of object shape and appearance. This determines the location of 3D objects with respect to a world system of coordinates as well as their motion in the virtual world. Object kinematics is governed by parent-child hierarchical relations, with the motion of a parent affects its child.

A robot arm can be made by combining the basic shapes like cylinders, cubes and cones. **Figure 8** shows the steps of robot forming. Each section which is added to the robot is subset of the previous section. Two links with an end-effector and a base has been designed based on the parent child rule. Simulated objects are rigid and formations are unchangeable by clash. Joystick limited capability was ignored third dimension and collision was simulated at two dimensions. Two intersecting walls are considered. Physical modeling is another important aspect that contains weight, inertia, roughness, hardness, softness and capability of changing in shape [13]. These features can make virtual world more realistic. Virtual walls are particular class of virtual objects that are not elastic. The real wall is rigid and cause large and sudden force feedback, so the hardness is considered in the range of 1000. Modeling of rigid surfaces is done by mass, spring and damper system to have same springy, inertial and damping specifications in real world [3]. **Figure 4** shows collision modeling between a cube and two intersecting walls. In addition transfer function between displacement and force is shown in Equation 4. The transfer function is damping oscillated system with two poles.

$$\begin{gathered}\frac{X}{F_x} = \frac{1}{Ms^2+Bs+K} \\ M = 1(kg), B = 2(N.s/m), K = 8(N/m)\end{gathered} \tag{4}$$

## 2.5 Non-linear Control Method

Feedback linearization method is one of the controller designing methods for nonlinear systems. In this method, U control rule should find a way to specify the initial condition of the system. The controller makes the system stable to reach the equilibrium point that system could behave like a linear system. First, we propose some theorem about nonlinear control [9].

La-Salle Theorem: Considering system $\dot{x} = f(x,t)$, $V(x)$is derivative and positive definite energy function. Meanwhile $\dot{V} < 0$or $-\dot{V}$ is not necessarily positive definite. If $\dot{V}(x)$ at point $x = 0$ is equal to zero then the equilibrium point is asymptotic stable for system$\dot{x} = f(x,t)$.

Vidyasagar Theorem: Supposing $G(s)$ is highly pure and highly stable, in this case:

If the input signal power $U$ is limited, the output signal $Y$ is evenly continues and it has limited energy range then both amplitudes of $Y$ and $\dot{Y}$ will be limited. But if only the range of input signal is limited then the output will be uniformly continuous.

Consider the robot system dynamic (Equation 2). The control law (Equation 5) is proposed for this system:

$$\tau = M\dot{v} + Cv + G - Ks \tag{5}$$

The parameters are defined according to Equations 6 to 8, And by applying them, closed loop system was formed like Equation 9.

$$\tilde{q} = q - q_d \tag{6}$$

$$v = \dot{q}_d - \Lambda\tilde{q}, \Lambda > 0 \tag{7}$$

$$s = \dot{q} - v = \dot{\tilde{q}} + \Lambda\tilde{q} \tag{8}$$

$$M\dot{s} + Cs + Ks = 0 \tag{9}$$

Now we are trying to prove the stability of the system. Lyapunov function and its derived function proposed is:

$$V = {}^{1}\!/_{2} s^T M s \rightarrow \dot{V} = -s^T K s \leq 0 \tag{10}$$

Considering the closed loop system structure and derived Lyapunov function as $s \rightarrow 0$ according to La-Salle theorem, the system will be asymptotic stable. In regard to Vidyasagar theorem, if the input signal power is limited then the output signal will depreciate. The parameter K will determine the speed of convergence of parameter s to zero. With high value of K the system reach to sliding mode faster. When the system goes to the sliding mode, the result is $\dot{\tilde{q}} = -\Lambda\tilde{q}$ . In this mode $\Lambda$ affects system. Regarding$s \rightarrow 0$, $\Lambda$ determines the speed of convergence of $\tilde{q} \rightarrow 0$. Additionally if the $\Lambda$ becomes bigger, $\tilde{q}$ ends to zero faster. This means angles of joints reach to the desire values sooner.

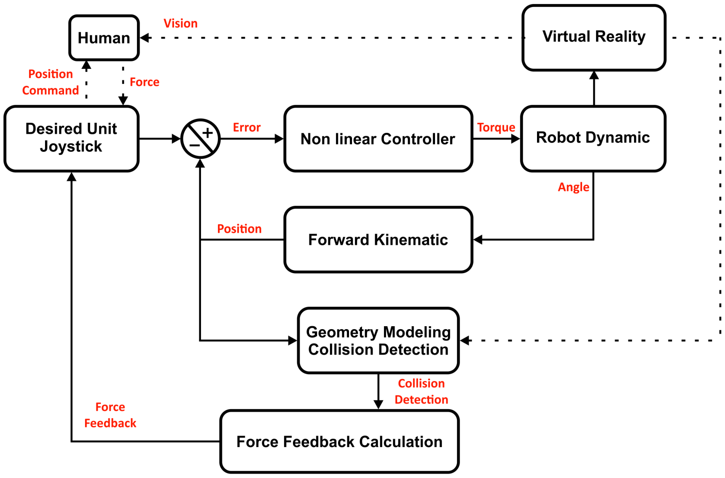

Figure 5. Teleoperation system

Figure 6. Interacting user with joystick

## 3. EXPERIMENTAL SETUP Experimental Setup

Teleoperation system which was analyzed here was shown in **Figure 5**. The system consists of the Human, Desired unit, Nonlinear controller, Robot, Virtual Reality, Forward kinematics, Geometry modeling, collision detection and force feedback calculation blocks.

First of all user receives force and image feedbacks from environment throughout joystick and screen, after that sends ideal position signal to robot. Position signal includes position and velocity in both x and y axis which are compare with real values of the robot dynamic output block. Error signal enters into the Slotine nonlinear controller and this block produces torque signals in both x and y axes which is sent to

Figure 7. 2-DOF revolute joint robot in VR

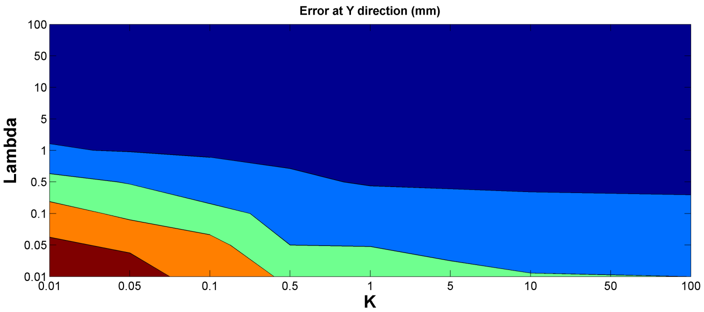

Figure 8. Grid-search on parameters, X Tracking error (mm)

the robot. Consequently the robot begins to move and the outputs are first and second joint angles. These angles are sent to The Virtual Reality block representing robot motions in virtual environment. At the same time these angles after converting to position signal by Forward Kinematic block, is transmitted to collision detection block. Then the collision detection block sends values of force responds to the force feedback calculation block considering Volume, size, distance and flexibility of bodies in defined environment and force response can be calculated with considering properties of bodies and contacts such as rigidity, stick, damping and flexibility. Finally force response is received by joystick and aware user delivering quality and quantity of collision. In addition Joystick calibrating can improve reality of task quality [15, 16]. **Figure 6** shows user interacting with joystick and **Figure 7** illustrates 2-DOF Revolute Joint Robot with two intersecting walls in Virtual Reality Environment (MATLAB©3D Simulink).

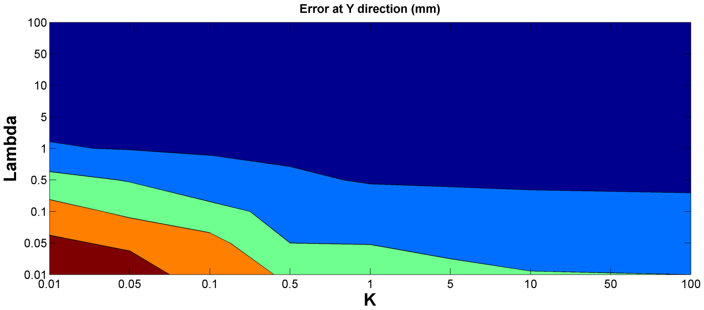

Figure 9. Grid-search on parameters, Y Tracking error (mm)

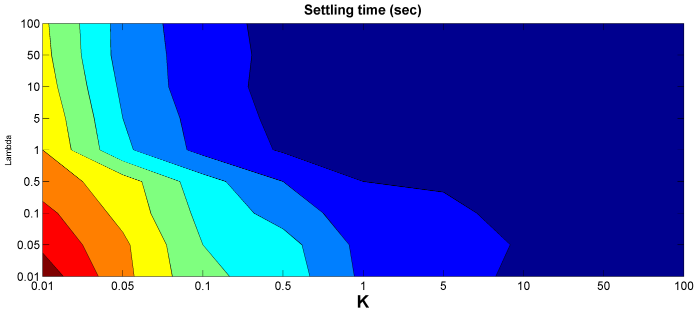

Figure 10. Grid-search on parameters, settling time (seconds)

## 4. RESULTS

All simulations were implemented by Simulink software, at a sample rate of 1 KHZ. Robot starts to move at Initial conditions $\begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{\pi}{2} \end{bmatrix}$. The master joystick was programmed to follow a fixed trajectory. Collision with wall occurred in x axis at 2.8 sec and 7 sec in y axis. A grid-search on K and

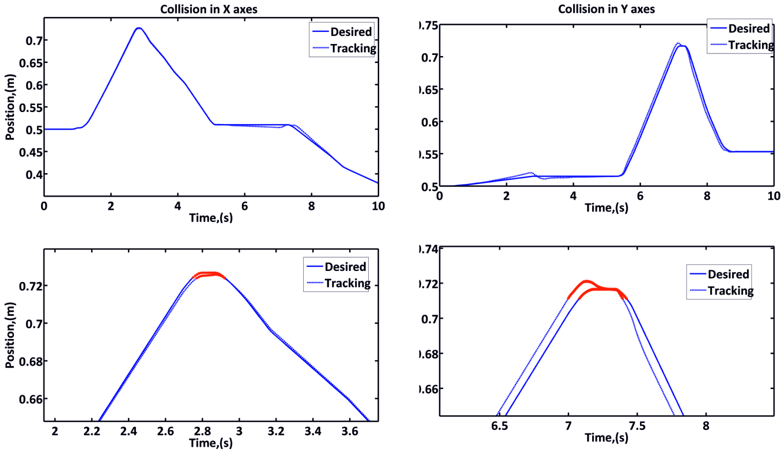

Figure 11. Robot collisions with x wall and y wall in 2.8 and 7 seconds. By K=10 and , results are acceptable. Tracking error is about 4mm and less than 0.2 sec settling time

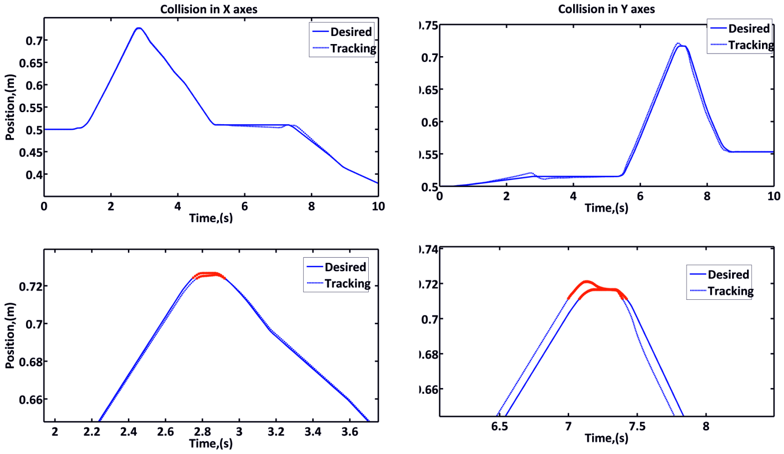

Figure 12. End-Effector's trajectory tracking in two dimensions

Λ parameters was carried out. Various pairs of K and Λ parameters were tried, and the one with the best tracking performance was picked up. Λ and K are varying from 0.01 to 100. **Figure 8**, **Figure 9** and **Figure 10** show grid-searches over K and Λ parameters. For K<0.5 and Λ<5, tracking was weak with more than 10mm and 20mm errors in x and y axes respectively. Settling time was more than 20 seconds. Increasing Λ has great effect to decrease error. Reversely increasing K causes better results in speed of system, and has less effect on error. Moreover, in despite of x axes, effect of gravity causes lower tracking performance in y. Finally K=10 and $\Lambda = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}$ are the best choice. **Figure 11** shows results. Tracking errors are 1.5mm and 4mm in x and y axes respectively and settling time is less than about 0.2 second. Eventually robot was successfully controlled. Moreover, **Figure 12** shows end-effector trajectory tracking in x and y axes. The control law has to be discontinuous across s. Since the implementation of the associated control switching is necessarily imperfect, this leads to chattering. Chattering in undesirable in practice, since it involves high control activity and further may excite high frequency dynamics neglected in the course of modeling. Finally, increasing in Λ parameter causes chattering.

## 5. DISCUSSION AND CONCLUSION

For a reliable teleoperation system, well designed controller has great role on system success. In this paper a sliding mode non-linear controller was designed and its optimal parameters were set. Force feedback joystick was used as master to deliver collision details to operator hand and drive 2-DOF slave robot in Virtual Reality environment. Moreover, vision feedback help to operator to better performance after collision with two inter-sectioned rigid walls. Λ parameters affect tracking error and K parameter impress on system speed. By grid-search method, optimal values of K and Λ cause to the best tracking performance, however control robot in y axes was difficult than x axes. Finally, 4mm error in y axes, 1.5mm error in x axes, and 0.2 seconds settling time were obtained in experiments.

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