MSU Fen Bil. Dergi., Cilt 6, Sayı 2, s 553-560 Araştırma Makalesi/ Research Article
MSU J. of Sci., Volume 6, Issue 2, p 553-560 DOI : 10.18586/msufbd.468332

Interface Design and Performance Analysis for a Haptic Robot

Tayfun ABUT[1], Servet SOYGÜDER[2]
[1] Makine Mühendisliği, Mühendislik-Mimarlık Fakültesi, Muş Alparslan Üniversitesi, Muş, Türkiye
[2] Makine Mühendisliği, Mühendislik Fakültesi, Fırat Üniversitesi, Elazığ, Türkiye
✉: tayfunabut@gmail.com

Received (Geliş): 05.10.2018 Revision (Düzenleme):25.10.2018 Accepted (Kabul): 26.10.2018.

ABSTRACT

Teleoperation systems are robot technologies that enable human-robot interaction. Haptic robots and interfaces are systems that allow you to feel, control, and organize objects in virtual environments that do not feel strength. With the development of computer hardware and human machine interfaces, researchers have incorporated virtual reality technology into interactive motion planning systems. Phantom omni robot has developed a haptic interface for interactive road planning verification and training. Based on the structural similarity between the six-degree-of-freedom Phantom Omni tactile device and the six-degree-of-freedom virtual slave robot arm, six DOF virtual robot rods driven by the Phantom Omni were modeled. Human robot interaction with the haptic-based virtual robot presented in the study was realized. As a result of the studies made, it is shown in the graphs that the reference master position, speed and force values are followed in great scale by the actual master robot-virtual slave robot by teleoperation. Consequently, a visual interface was created in this study and the position, velocity, and force control were performed by teleoperation. The performance results were given graphically and were found to be successful.

Keywords: Teleoperation, Haptic, Virtual Reality, Human-Robot Interaction

Bir Haptik Robot için Arayüz Tasarımı ve Performans Analizi

ÖZ

Teleoperasyon sistemleri insan-robot etkileşimini sağlayan bir robot teknolojisidir. Haptik robotlar ve ara yüzler kuvveti hissetmemize yarayan, sanal ortamdaki cisimlere dokunma, onları hissetme, kontrol etme ve düzenlemeye imkân veren sistemlerdir. Bilgisayar donanımı ve insan makine arayüzlerinin geliştirilmesiyle, araştırmacılar sanal gerçeklik teknolojisini etkileşimli hareket planlama sistemlerine dahil etmişlerdir. Phantom omni robotun interaktif yol planlaması, doğrulaması ve eğitimi için haptik bir arayüz geliştirilmiştir. Yapılan çalışmada, altı serbestlik dereceli Phantom Omni dokunsal cihaz ile altı serbestlik dereceli sanal slave robot kolu arasındaki yapısal benzerliğe dayanarak, Phantom Omni tarafından yönlendirilen altı DOF sanal robot kolu modellenmiştir. Çalışmada sunulan haptik tabanlı sanal robot ile insan robot etkileşim gerçekleştirilmiştir. Yapılan çalışmalar sonucunda gerçek master robot–sanal slave robotlar arasinda teleoperasyon ile referans konum , hız ve kuvvet değerleri büyük ölçüde takip ettiği grafiklerde gösterilmistir. Sonuç olarak bu çalışmada görsel arayüz oluşturulmuş ve teleoperasyon ile konum ve hız kontrolü gerçekleştirilmiştir. Performans sonuçları grafiksel olarak verilmiştir ve başarılı olduğu görülmüştür.

Anahtar Kelimeler: Teleoperasyon, Haptik, Sanal gerçeklik, İnsan-robot etkileşimi

INTRODUCTION

Robotics is a relatively young area of modern technology that goes beyond the boundaries of traditional engineering. Virtual reality and haptic systems today have become quite popular research subjects. Applications are performed in many fields using virtual reality and haptic technology. In addition, as both controller design and device design, haptic-teleoperation systems have become an active research topic in recent years. Prior to actual work, developing robotic applications in the virtual environment provides reliable and rapid testing. Such applications with virtual reality can prevent potential damage during development and testing. Teleoperation systems are robot technologies that enable human-robot interaction. It means the ability to feel the natural or artificial mechanical environment through haptic touch. Haptic devices are manipulators that interact with the user. The device senses the user's movements and forces, and makes the user feel virtual or remote environmental characteristics. With the help of force and surface information feedback, haptic technology has increased the sense, and so the precision, of remote presence in remote control operations and the precision of on-site robotic works. The usage areas of haptic-teleoperation systems are quite extensive. Robotic surgery, medical, defense industry, nuclear studies and simulators etc. are some of them [1-8]. The control of these systems is a matter that needs to be paid attention heavily in relation to the task and the area of use. Phantom haptic interfaces, first designed by Massie and Salisbury

(1994), later marketed by the company Sensable Technologies, have widespread use with its wide operating area, low inertia applications, low friction and precise position characteristics [9]. This device is one of the first haptic devices developed and marketed by the company Sensable Technologies [10]. The small size, relatively low cost and innovations that simplify the presentation of haptic information of the Phantom-interfaced device are some reasons for choosing it. This haptic device provides feedback by simulating touching at high quality from a single point rather than viewing information from many different points. By applying pressure on the pen with three small motors, it provides force feedback to the user. For example, the user can feel the elasticity of a virtual balloon or the hardness of a brick wall. With a pen, it can customize any object close to reality, that is, near the same.

The Phantom Omni electromechanical haptic device is used in many applications. For example, it is frequently used in applications of rehabilitation, tele-robotics, teleoperation, entertainment, etc. [11-13]. Çavuşoğlu, and Feygin studied the kinematic and dynamic analysis of the Phantom 1.5 model, in which friction forces were neglected [14]. Çavuşoğlu et al. examined the haptic interface of the Phantom 1.5 model electrically and mechanically in the virtual environment and teleoperations, and studied the development of high performance control structures [15]. Silva et al. studied kinematics and applicability for phantom robots [16]. Pere et al. (1996) developed a haptic device called Rutgers Master II (RMII) to perform assembly tasks at a desktop-based virtual assembly workshop named VShop at Rutgers University [17]. Another system combined the PHANTOM haptic device with a pin-array touchscreen for area-based haptic rendering and used the system by point-based haptic rendering in a user's work [18]. Boeing's Department of Mathematics and Computer Technology (M & CT) has also worked with SensAble to produce a desktop virtual prototyping application for testing PHANTOM 3.0 / 6DOF with VPS collision and communication response software (McNeely et al. 1999)[19]. Hwang et al. proposed a human-computer collaborative system for robot path planning [20]. In this method, the roles of the users are to select a possible solution path, to define the configurations along the way in confined spaces, and to supply these configurations as sub-targets to verify the presence of a non-collision path. Yuan and Yang provided an interactive assembly planning method that provides an intuitive hand-based interface for human operators to perform direct assembly operations in a virtual environment [21]. Mikchevitch et al. proposed a practical planning system for 2D assembly tasks at micro / nano scale [22]. Mikchevitch et al. also implemented a road planning method in the VR environment for flexible components in another study [23]. Freire et al. developed a multimedia environment used in the field of education to simulate robot arm operations [24]. Miner et al. presented a Virtual Reality (VR)-based robotic control system that provides operators with an educated tool to run and work with complex robot systems using voice command interaction in an intuitive and low-cost manner [25]. Such systems are very useful for assembly process design [26-30].

In this context, one-way and two-way control in robotic applications with force and torque feedback have been actively researched and studied recently in the field of robotics. In this study, the kinematic and dynamic models of the device were obtained in order to get performance from the Phantom Omni haptic device, the system was tried to be identified by determining the points in the study area of the device, teaching these points and testing trajectory tracking. The parameter values used when creating the virtual slave robot are factory production dimensions of the Phantom Omni haptic robot found in our laboratory. A real-time bilateral-teleoperation study was performed between a 6-degree-of-freedom master Phantom Omni haptic robot and a virtual 6-degree-of-freedom robot. A visual interface is designed for visual feedback of movements of the slave robot controlled by Phantom omni robot. A visual interface is designed for the Phantom omni robot to provide the visual feedback for interactive road planning, verification and training. In this study, based on the structural similarity between the six-degree-of-freedom Phantom Omni haptic device and the six-degree-of-freedom virtual slave robot arm, a six DOF virtual robot arm driven by the Phantom Omni were modeled. The human robot interaction was realized with the haptic-based virtual robot presented in the study. The performance of the controller has been investigated by adding both process noise and measurement noise to the system. As a result of the study done, it is shown in the graphs that the reference position, velocity and force values are followed in great measure by teleoperation between the real master robot and the virtual slave robot. As a result, in this study, a visual interface was created and position, velocity and force controls are performed with teleoperation. Performance results were given graphically and seen to have been successful.

MATERIAL and METHOD

Mathematical model of the haptic system

In this section, the kinematic (forward kinematic model, inverse kinematic model, Jacobian matrix) and dynamic analysis of the haptic system have been performed.

Forward Kinematic (Kinematic Analysis)

Forward kinematics can also be defined as the process of determining where the robot is in Cartesian space according to given joint variables. For forward kinematics, the Denavit-Hartenberg method was used [31]. The robot's forward kinematics deals with the relationship between the positions, velocities and accelerations of the links forming the robot [32].

$$x = Sin\theta_1(l_1.Cos\theta_2 + l_2Sin\theta_3) \quad (1)$$

$$y = l_2Cos\theta_3 + l_1Sin\theta_2 \quad (2)$$

$$z = Cos\theta_1(l_1Cos\theta_2 + l_2Sin\theta_3) \quad (3)$$

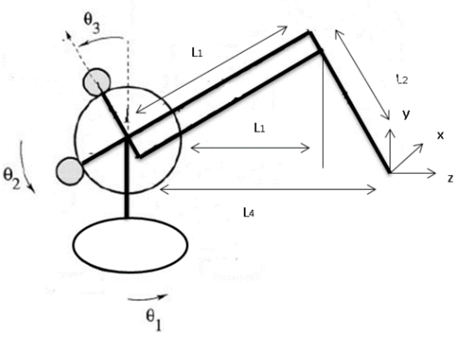

Figure 1. Phantom Omni Haptic robot's free body diagram [33]

Inverse Kinematic

Inverse kinematics calculations have an important place in the robot control processes. Inverse kinematics is the process of finding the values of joint variables according to given position and orientation data of the end function. Calculation of joint torques for inverse kinematic solution actuators is a key issue in processes such as real-time control and trajectory planning [34-35].

$$\theta_1 = -a\tan 2(y/x) \quad (4)$$

$$\theta_2 = \phi - \gamma \quad (5)$$

$$\theta_3 = \frac{3\pi}{2} - \cos^{-1}\left(\frac{L_1^{\,2} + L_2^{\,2} - k^2}{2L_1L_2}\right) \quad (6)$$

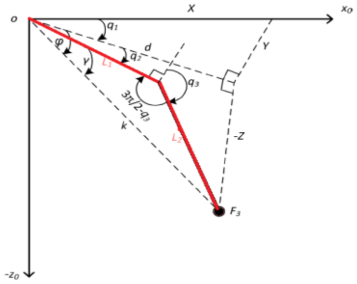

Figure 2. Inverse kinematic figure of Phantom Omni haptic robot [36]

Jakobian Matrix

The movement of each joint must be coordinated so that the robot can move at a specified speed in the specified direction. It is known that the position and rotation of the robot depends directly on the movement of the joints. The Jacobian matrix determines the real working area of the device, saves from singular points and shows the applicability of the device. Equation 11 gives the Jacobian matrix of the haptic robot.

$$k = \sqrt{x^2 + y^2 + z^2} \quad (7)$$

$$\phi = \cos^{-1}\left(\frac{d}{k}\right), z \le 0$$
$$\phi = -\cos^{-1}\left(\frac{d}{k}\right), z \succ 0 \quad (8)$$

$$d = \sqrt{x^2 + y^2} \quad (9)$$

$$\gamma = \sin^{-1}\left(\frac{L_2\ \sin(\frac{3\pi}{2} - \theta_3)}{k}\right) \quad (10)$$

$$J_{m,s} = \begin{bmatrix} -\cos\theta_1(l_2sin\theta_3 + l_1\cos\theta_2) & l_2sin\theta_1sin\theta_2 & \text{-}l_2sin\theta_1\cos\theta_3 \\ 0 & l_1\cos\theta_2 & l_2sin\theta_3 \\ -l_2sin\theta_1sin\theta_3\text{-}l_1sin\theta_1\cos\theta_2 & l_1sin\theta_2\cos\theta_1 & l_2\cos\theta_1\cos\theta_3 \end{bmatrix} \quad (11)$$

Equations of Motion the Master and Slave Robot

To obtain the system's dynamic equations, Lagrange-Euler [37] method was used. Control of the robots was carried out using the equations of the first three axes, which are the basic axes of the robots.
The motion equations for master and slave robots are given below.

$$M_m(q_m)(\ddot{q}) + C_m(q_m, \dot{q}_m)(\dot{q}_m) + G_m(q_m) = \tau_h + \tau_m \quad (12)$$

$$M_s(q_s)(\ddot{q}) + C_s(q_s, \dot{q}_s)(\dot{q}_s) + G_s(q_s) = \tau_s - \tau_e \quad (13)$$

q_i, $\dot{q}_i$, $\dot{q}_i$ and τ_i represent position, velocity, acceleration and control torque, respectively. The $i \in \{m, s\}$ indices represent master and slave robots, respectively. $M(q_i) \in R^{3*3}$ is a positive definite symmetric matrix and shows the inertia matrix; $C(q_i) \in R^{3*3}$ the matrix of Coriolis and centrifugal forces; $G(q_i) \in R^{3*3}$ the weight forces. τ_m, τ_s are the torques acting on the master and slave robots, respectively. τ_h and τ_e represent the torques corresponding to the disturbing forces applied by the user and affecting the system from surrounding. As shown in Figure 3, the Phantom Omni haptic robot has 6 rotary joints, but the first 3 joints are active, 3 wrist joints are passive, that is, not driven by a motor, but the robot has 6 encoders. Table 1 showed the Phantom Omni haptic robot's physical parameters.

Figure 3. Phantom Omni Haptic robot and its rotation axes

Tablo 1. Parameters of Phantom Omni Robot

Description& Symbol	**Units &Value**
Gravity	~1,47 g
Dimension	~168W*203D mm
Inertia (*I*)	~45 g
Position resolution ($\boldsymbol{\theta}$)	~0.055 mm
Maximum improvement force (Fmax)	3.3 N
Force feedback (F)	x, y, z
Position measurement	x,y,z Pitch,roll,yaw
Interface	Parallel port
Supported Platforms	Intel based -PCs

Interface Design of the Slave Robot

The physical parameters of the virtual slave robot were obtained from the factory production dimensions of the 6-degree-of-freedom Phantom Omni haptic robot in our laboratory that we used in real time (Table 1). The CAD model of the virtual robot was drawn in a solid modeling program and a three-dimensional (3D) model was created (Figure 4).

Controller Design of the Haptic System

PD based Computed torque control (PD-CTC) was used for position control of the haptic system and traditional PID (proportional integral derivative) control method was used for force control. In the control systems used, it is aimed that the output value of the system follows the target (reference) value. The difference between the target (reference) output value in the system and the current system output value is called the error value. With the controllers applied to the system, this error is tried to be minimized.

Variable parameters of the slave robot are transferred to Matlab package program, VR Sink block is used to create the 3D visual of the system and necessary scene and light settings are realized. The visual interface is designed for the virtual robot in this program.

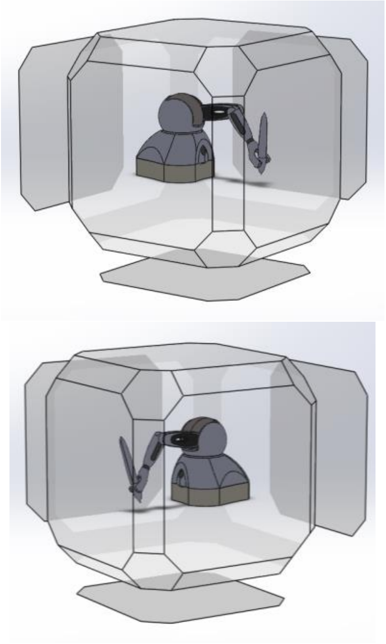

Figure 4. Generated solid model of the Phantom omni haptic robot

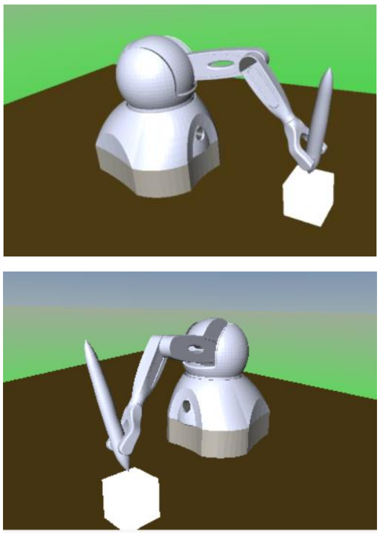

Figure 5. Created visual interface for the Phantom omni haptic robot

Force Control

In this study, PID (proportional integral derivative) control method was used for force control. Although the PID (proportional integral derivative) control method is an old method used in many applications, it performs well [38]. Because it is relatively easy to calibrate compared to other controllers and has a simple control scheme, its use is widespread. Equation 14 shows the basic structure of the PID control method [39].

$$u(t) = K_p e(t) + K_I \int_0^{\tau} e(t)\,dt + K_D \frac{d}{dt} e(t) \qquad (14)$$

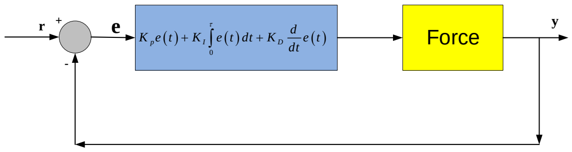

Figure 6. Force with PID feedback's block diagram

u is called the controller output, K_p the proportional gain K_I the integral gain, K_D the derivative gain, and *e* the error signal. Figure 6 shows the block diagram of the system with PID feedback. In this study, the Ziegler-Nichols method presented by John G. Ziegler and Nathaniel B. Nichols was used to find the PID coefficients, and also closed loop control type was used in this method [39]. Table 2 shows the general control parameters of Ziegler-Nichols method**.**

Table 2 Control parameters obtained by the Ziegler-Nichols method

Control	K_P	K_I	K_D
P	0.5*K_{cr}	~1,47 g	0
PI	0.4*K_{cr}	0.8*P_{cr}	0
PID	0.6*K_{cr}	0.5*P_{cr}	0.125*P_{cr}

Motion Control

In this study, PD based computed torque control (PD-CTC) control method is used for motion control due to nonlinear behavior of the system[40]. The computed torque control method is a robust and nonlinear controller commonly used in the control of robots. This control system calculates the required torque values for the system using the nonlinear feedback control law based on feedback linearization [41]. Figure 7 shows PD based computed torque control (PD-CTC) block diagram.

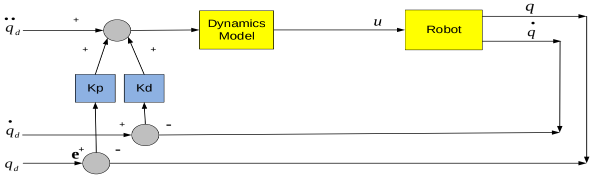

Figure 7. Block diagram of PD-Computed torque control (PD-CTC)

Figure 8 shows the block diagram of a two-way (bilateral) teleoperation system. The PD-Computed torque control method was used in motion controls of 6-degree-of-freedom master and slave robots.

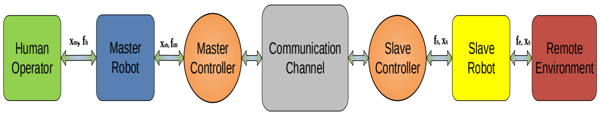

Figure 8. Block diagram of two-way (bilateral) teleoperation system

The purpose of this control is to follow the reference trajectory generated by the master. Furthermore, it is to track the position and velocity values generated by the master robot having the minimum position and velocity error. And in force controls, PID control method was used. The aim here is to obtain the desired force values.

EXPERIMENTAL RESULTS

Experimental studies have been carried out in this section using the motion equations of master and slave robots. The designed interface provides visual feedback to the user. System's control variables are the joint angles and the force values. The basic axes of robots, $\theta_1,\theta_2,\theta_3$ that is, the first three axes were controlled. Simulation results obtained from system control are given in the following graphs. $\tau_h = J_m{}^T F_h$ and are taken as $\tau_e = J_s{}^T F_e$. The relationship between the human operator and the environment is modeled as a box in a virtual environment and as a mass-spring-damper model for modeling.

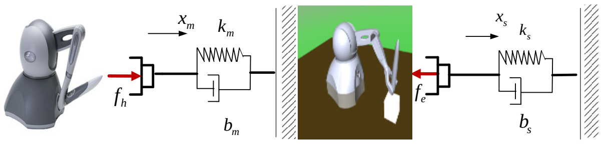

Figure 9. The physical model of the force between the human operator and the environment

In Figure 9, the forces between the human operator and the environment are shown as a physical model modeled as a mass-spring-damper system. F_e force is derived from interaction with the virtual wall in the xy plane at the distance $z_r = 0.1$ m. $F_e = k(z_r - z) + b(\dot{z}_r - \dot{z})$ b=2 Ns/m represents the damping coefficient and k=10 N/m is the spring constant, and F_e represents the emerging environmental force. z_r shows the reference position of the robot and z shows the actual position. $F_h = k(q_m - q_s) + b(\dot{q}_m - \dot{q}_s)$ b=1 Ns/m represents the damping coefficient and k=5 N/m is the spring constant, F_h represents the emerging force.

In this section, position, velocity and its control are realized by bilateral haptic teleoperation between the master robot and the virtual slave robot. Two robots with the same kinematic characteristics were used in the teleoperation system created in the real-time laboratory study. In communication of the system, a Quanser Q8 USB data acquisition management board with MATLAB Real-Time WorkshopTM Toolbox and a WinConTM / RTXTM real-time control system were used. In addition, the power supplies, microprocessor for the robot setup and data acquisition card for data collection were gathered. After the necessary connections are made, it is aimed that the virtual slave robot will go to the reference values and the follows the position while generating the reference position with the master robot. The angular position values obtained from the outputs of the master robot to control the slave robot were used as inputs of the virtual slave robot dynamics to control of the slave robot. The result of the interaction of virtual slave robot with the virtual environment was obtained by controlling the forces F_e that acted on the slave robot from surroundings and F_h that acted on the human operator side. Figure 10 and Figure 12 show the position and velocity graphs obtained using the PD based computed torque control (PD-CTC) method of the joints.

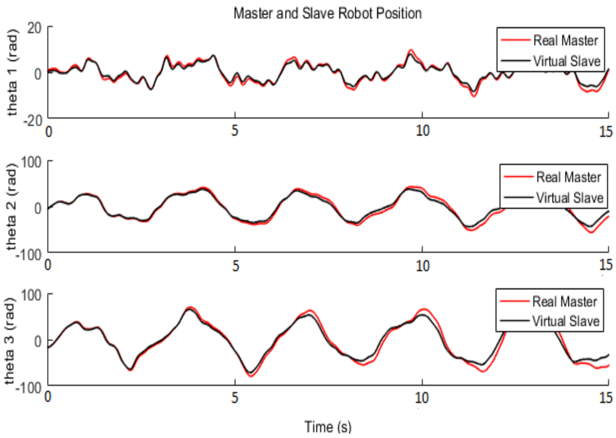

Figure 10. Position graphics for theta1, theta2 and theta3

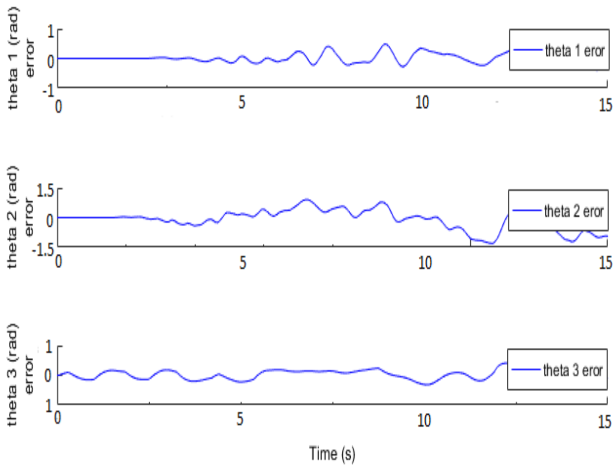

Figure 11. Position error graphics for theta1, theta2 and theta3

Figure 11 and 13 respectively showed the position and velocity error graphics. The experimental study period was carried out as 15 seconds. The forces generated by the interaction of the slave robot with the environment are the forces felt by the human operator physically as a result of the transmission to the master-robot with the torque-force sensor feedback (Figure 14). In Fig. 14, the human operator (τ_h) and environmental torque (τ_e) graphs obtained by using the PID control method when the slave robot interacts were shown.

Experimental result graphs showed that the position, velocity and force controls were successfully performed in the teleoperation system consisting of master and slave robots.

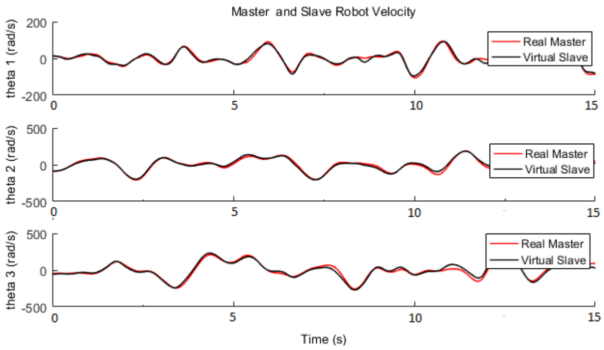

Figure 12. Velocity graphics for theta1, theta2 and theta3

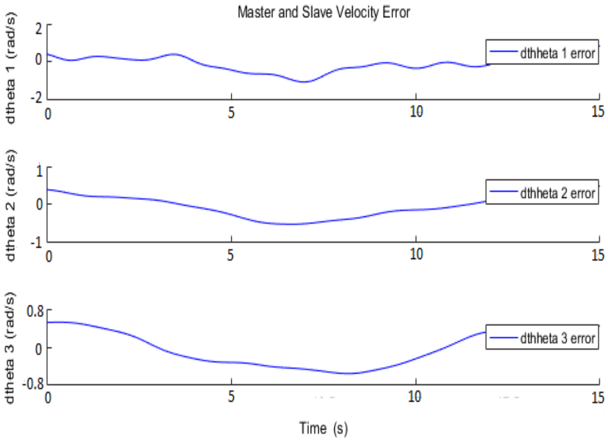

Figure 13. Velocity error graphics for theta1, theta2 and theta3

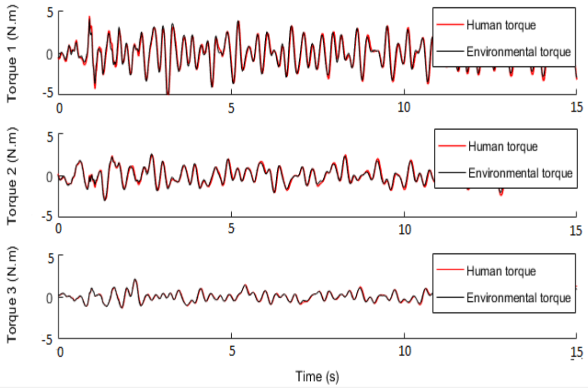

Figure 14. Human-operator and environmental torque values when the slave robot interacts

CONCLUSION

In this study, six DOF haptic robots were introduced and the applicability in determining the performance of the device was calculated. Kinematic and dynamic analysis of the device was carried out. While dynamic analysis was being performed, dry and viscous friction forces acting on the system are also calculated. In addition, the aim of existing experiments is to confirm mathematical models and verify the performance of the device. A real-time bilateral-teleoperation study was conducted between the 6-degree-of-freedom Phantom Omni haptic robot and the virtual 6-degree-of-freedom robot. As a result of the experimental studies, it is shown in the graphs that the reference position, speed and velocity values are followed in great measure by teleoperation between the real master robot and the virtual robot. It has been seen that the designed and applied control algorithms were successful on the system. As a result, with the methods used in the aimed two-way teleoperation studies, controls were realized, a virtual environment was created and two-way motion and force control were performed by teleoperation and the applications of the system in the real environment were realized.

ACKNOWLEDGMENTS

This work was supported by Firat University Scientific Research Projects (FÜBAP) 2015, MF. within the scope of the project no:13.15.

ORCID

Tayfun ABUT http://orcid.org/0000-0003-4646-3345
Servet SOYGÜDER http://orcid.org/0000-0002-8191-6891

REFERENCES

[1] Vertut, J., Coiffent, P. Teleoperation and Robotics. Evolution and Development. Kopan Page. London, 1985.

[2] Goertz, R.C., Thompson R.C. Electronically controlled manipulator. Nucleonics, 12:11 46-47, 1954.

[3] Katsura S., Iida W., Ohnishi K. Medical mechatronics An application to haptic forceps, Annual Reviews in Control, 29:2 237-245. 2005.

[4] Veras E., Khokar K., Alqasemi R., Dubey R. Scaled telerobotic control of a manipulator in real time with laser assistance for adl tasks. Mechatronics and its Applications International Symposium on Mechatronics and its Applications, March 2009.

[5] Song G., Guo S. Development of a novel tele-rehabilitation system. Proceedings of the 2006 IEEE International Conference on Robotics and Biomimetics, p.785-789 2006.

[6] Wang P., Becker A.A., Jones I.A., Glover A.T., Benford S.D., Greenhalgh C.M., Vloeberghs M. A virtual reality surgery simulation of cutting and retraction in neurosurgery with force-feedback, Computer methods and programs in biomedicine, 84 11-18, 2006.

[7] Fahlbusch St., Mazerolle S. Breguet JM., Steinecker A., Agnus J., P´erez R., Michler J. Nanomanipulation in a scanning electron microscope, Journal of Materials Processing Technology, 167:2 371-382, 2005.

[8] Park K., Bae B., Koo T.A haptic device for PC video game application, Mechatronics, 14:2 227-235, 2004.

[9] Massie T.H., Salisbury J.K. The phantom haptic interface: A device for probing virtual objects. In Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems, 55:1 295-300, 1994.

[10] Sensable Technologies Corporation, http://www.sensable.com/.

[11] Diolaiti N. Melchiorri C. Teleoperation of a mobile robot through haptic feedback, IEEE Int.Workshop on Haptic Virtual Environments and Their Applications, 2002 67-72, 2002.

[12] Nygaard A. High-Level Control System for Remote Controlled Surgical Robots Haptic Guidance of Surgical Robot, Master thesis of Science in Engineering Cybernetics, Department of Engineering Cybernetics, Norwegian University of Science and Technology, 2008.

[13] Dominguez-Ramirez O.A., Parra-Vega V. Texture, roughness, and shape haptic perception of deformable virtual objects with constrained Lagrangian formulation. In Intelligent Robots and Systems, IEEE/RSJ International Conference on 4 3106-3111, 2003.

[14] Cavusoglu M.C., Feygın D. Kinematics and dynamics of PHANToM(TM) model 1.5 haptic interface. (Tech. Rep.). University of California at Berkeley, Electronics Research Laboratory Memo M01/15, 2001.

[15] Cavusoglu M., Feygın D., Tendıck F. A Critical Study of the Mechanical and Electrical Properties of the PHANToM Haptic Interface and Improvements for High Performance Control. Presence: Teleoperators and Virtual Environments, 11:6 :555-568, 2002.

[16] Silva A.J., Ramirez O.A.D., Vega V.P., Oliver J.P.O., PHANToM Omni Haptic Device: Kinematic and Manipulability, Electronics, Robotics and Automotive Mechanics Conference, CERMA, 193-198, 2009.

[17] Pere E, Langrana N, Gomez D, Burdea G.C. Virtual mechanical assembly on a PC-based system. In: Proceedings of the ASME design engineering technical conference and computers in engineering, Irvine, California, 1996.

[18] Kyung K.U., Park J., Kwon D.S., Kim S.Y. Real-Time Area- Based Haptic Rendering for a Palpation Simulator. In M. Harders and G. Sz´ekely, editors, Biomedical Simulation, Springer Berlin Heidelberg, Berlin, Heidelberg, 4072:15 132-141. 2006.

[19] McNeely W.A., Puterbaugh K.D., James T.J. Six degree-offreedom haptic rendering using voxel sampling. Six degree-of-freedom haptic rendering using voxel sampling. In: ACM SIGGRAPH 2005 Courses. ACM, p.42, 2005.

[20] Tsui P.H., Lin L.Y., Chang C.C., Hwang J.J., Lin J.J., Chu C.C., Chen C.N., Chang K.J., Chang C.C. Arterial pulse waveform analysis by the probability distribution of amplitude. Physiological Measurement, 8:8 803-812, 2007.

[21] Yuan X.B., Yang S.X. Interactive assembly planning with automatic path generation. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, 3965-3970, 2004.

[22] Mikchevitch A., Leon J.C., Gouskov A. Path planning of an AFM-based nanomanipulator using virtual force reflection. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, 577-582, 2004 .

[23] Mikchevitch A., Leon J.C., Gouskov A. Path planning for flexible components using a virtual reality environment. In: 5th IEEE International Symposium on Assembly and Task Planning, 247-252, 2003.

[24] Freire J.C., Jr., De Lima J.V., Neves R.A., De Sena G.J. A multimedia environment for supporting the teaching of robotics systems. In: Proceedings of the 24th International Conference on Distributed Computing Systems Workshops, 280-285, 2004.

[25] Miner N.E., Stansfield S.A. Interactive virtual reality simulation system for robot control and operator training. In: Proceedings of the 1994 IEEE International Conference on Robotics and Automation, 1428-1435, 1994.

[26] Abut T., Servet S. Real-time control of bilateral teleoperation system with adaptive computed torque method. Industrial Robot: An International Journal, 44:3 299-311, 2017.

[27] Soyguder S., Abut T. Haptic industrial robot control with variable time, Industrial Robot: AnInternational Journal, 43:4 390-402, 2016.

[28] Abut T., Servet S. Zaman Gecikmeli İnsan-Makine Etkilesimli Teleoperasyon Sisteminin Kontrolü. Fırat Üniversitesi Mühendislik Bilimleri Dergisi, 30 1193-202, 2018.

[29] Abut T., Servet S. Haptic industrial robot control and bilateral teleoperation by using a virtual visual interface, 2018 26th Signal Processing and Communications Applications Conference (SIU). IEEE, 2018.

[30] Abut T., Servet S. Motion control in virtual reality based teleoperation system. In Signal Processing and Communications Applications Conference (SIU), 23th IEEE, 2682-2685, 2015.

[31] Denavit J., Hartenberg R.S. A kinematic notation for Lower-pair mechanisms based on matrices, ASME Jappl. Mechan, 215-221, 1955.

[32] Bingül Z., Küçük S. Robot Tekniği I, Birsen Yayınevi, 104-200, 2005.

[33] Abut T. Altı Serbestlik Dereceli Haptik Robot ile Teleoperasyon ve Sistem Dinamiği, Yüksek lisans Tezi, Fırat Üniversitesi, Elazig, 2015.

[34] Asada H., Slotine J.J.E. Robot Analysis and Control, Wiley-Interscience Publication, USA, 1986.

[35] Kerrow F.J.M. Introduction to Robotics, Addison-Wesley Publishing, USA, 1991.

[36] Sreelakshmi M., Subash T. D. Haptic Technology: A comprehensive review on its applications and future prospects. Materials Today: Proceedings, 4:2 4182-4187, 2017.

[37] Hazewinkel M. Lagrange equations (in mechanics)", Encyclopedia of Mathematics, Springer, ISBN 978-1-55608-010-4, 2001.

[38] Abut T., Servet S. Alli H. Gercek Zamanli Alti Serbestlik Dereceli Haptik Bir Robot ile Sanal Robotun Teleoperasyonu' UMTS 2015 Bildiri Kitabı, Izmir, 2015b.

[39] Ziegler J.B. Nichols N.B. The classic original paper: Optimum settings for automatic controllers", ASME Transactions, 64 759-768, 1942.

[40] Tuong D.N., Seeger M., Peters J. Computed torque control with nonparametric regression models", Proceedings of the 2008 American Control Conference (ACC), Seattle, 2008.

[41] Middleton R.H. Goodwin G.C. Adaptive computed torque control for rigid link manipulators, Systems and Control Letter, 10 9-16, 1988.