Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2013) 21: 493 – 499

doi:10.3906/elk-1110-52

7-DOF Haptic device and interface design

Özgür BAŞER, Erhan İlhan KONUKSEVEN*
Department of Mechanical Engineering, Middle East Technical University, 06800 Ankara, Turkey

Received: 25.10.2011 • **Accepted:** 24.11.2011 • **Published Online:** 22.03.2013 • **Printed:** 22.04.2013

Abstract: In this study, the developed 7-DOF haptic device (HaP-7) and its virtual reality interface are presented. The design issues, design constraints, and alternative design configurations are discussed and the potential advantages of the HaP-7 are put forward. The kinematic model of the proposed device looks like a simplified human arm kinematic model. The redundant characteristic of the device provides larger workspace and allows for appropriate posture selection for the purposes of maximization of the rigidity, transparency and stability, while minimizing the inertia and power consumption in addition to the singularity and obstacle avoidance optimization.

Key words: Haptic device design, virtual reality, force feedback, visual feedback

1. Introduction

Haptic devices are used to provide 3- or 6-dimensional (3D/6D) data transfer between the users and computers in virtual reality (VR) applications [1]. They enable the users to touch the models designed in the virtual environment. Haptic devices sense the motion and force applied to the virtual objects by the user in its workspace and produce force feedback to the user. The force feedback is computed based on the virtual models [2]. Due to the force feedback capability, VR applications are widely used in the areas of engineering, medical operations, teleoperation, welfare, and entertainment through the development of computers and robotic technology [3].

The most basic parameter in haptic device design is the number of degrees of freedom (DOF). A haptic device can include one or more degrees of freedom. At least 3 DOF are required to produce 3D force feedback. Since some VR applications need 3D torque feedback, a haptic device must have 6 or more DOF to reflect all of the 3D force and 3D torque feedback. Higher degrees of freedom may increase the area of applications and improve the performance of the haptic devices. In this study, apart from the existing commercial 6-DOF devices, a 7-DOF redundant haptic device is designed and its graphical user interface and implementation are presented.

2. Haptic devices in literature

There are 3 types of design configurations in the literature: mechanical arm, cable driven, and magnetic levitation haptic devices [4,5]. In order to simulate the virtual models effectively, for the haptic devices it is desired that the working volume, end point force/torque, rigidity, and resolution be maximized while the backdrive friction, apparent mass, and backlash be minimized. These are considered as design parameters for haptic devices.

*Correspondence: konuk@metu.edu.tr

All of the required characteristics mentioned above can be achieved by optimizing the design parameters of the mechanical arm haptic device. Utilization of cable-capstan drive mechanisms is generally preferred between the actuators and links to cancel the mechanical backlash in this type of device [6]. In the cable-driven devices, the haptic handle is connected to the actuators by the cables directly. They cannot provide high force/torque due to the cable weakness and large workspace due to the cable interference. Since vibration handicaps occur during operation, they do not have high sensitivity. Even though magnetic levitation devices have high sensitivity, they have quite a small workspace due to their design concepts. When the potential designs are compared, it can be concluded that the most suitable configuration is the mechanical arm design. In this study, the design of the device is based on the mechanical arm configuration, including cable-capstan mechanisms.

3. Design and superiority of HaP-7

The mechanical arm device can be considered as a robot manipulator. A manipulator configuration can be purely serial or parallel mechanisms. Even though the parallel structures have high stiffness and their positioning accuracy is quite high, serial manipulators have larger workspace than the parallel mechanisms. The advantages of these mechanisms can be incorporated by combining them in one configuration, which is called a hybrid mechanism [2]. In this study, a hybrid type of configuration is used for the 7-DOF haptic device (HaP-7) design (Figure 1). In the design, 2 separate 3-DOF serial linkages exist at the base and at the tip of the device. These 2 serial configurations are connected to each other by 1 parallelogram. In order to minimize the apparent mass of the device, the static balance is performed for all moving parts, excluding the haptic handle. For this purpose, the fourth motor is used as a counterweight so that the static balance is achieved without increasing the inertia (Figure 1).

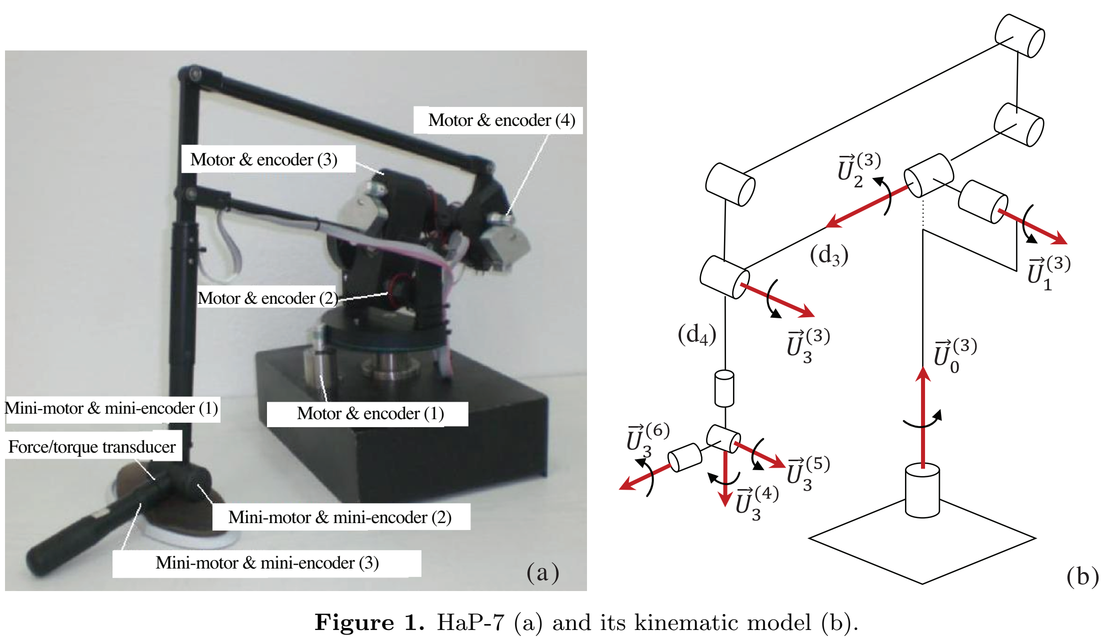


Figure 1. HaP-7 (a) and its kinematic model (b).

Since the HaP-7 has a redundant joint, it enables an approximate 20% increase in the workspace without compromising the other design criteria [4,5]. Moreover, the redundancy enables it to reach any point with different postures in the workspace. This capability can be used to improve the performance. The optimal posture can be selected for any target performance using the appropriate optimization techniques. These targets can be maximization of the stiffness, transparency, stability, minimization of the inertia, power consumption, singularity, or obstacle avoidance. Each target can be considered as the superiority of the HaP-7.

The redundant manipulators may reflect different stiffness characteristics based on the selected posture due to the flexibility of the links and joints. The most appropriate posture should be selected for the high precision applications. For this purpose, the nonlinear least square optimization can be applied to find the appropriate redundant joint angle value by minimizing the end point deflection of the HaP-7. The cost function of the problem can be represented in terms of applied force F, Jacobian matrix J, and diagonal joint stiffness matrix $K_\theta = Diag\left[K_{\theta 1}, K_{\theta 2}, \ldots, K_{\theta 7}\right]$:

Find $\theta_{redundant}$ to minimize the total driving torques $\rightarrow f\left(\theta_{redundant}\right) = \frac{F}{J^{-T} K_\theta J^{-1}}$.

Recently, the performances of haptic devices are preferred for evaluation by means of their transparency [7]. The optimal posture can be selected in order to increase the transparency of the device. Optimal optimization selection enables the minimization of the parasitic forces coming from the dynamic and gravitational effects of the device. The cost function of the problem can be represented in terms of mass matrix M, centrifugal-Coriolis matrix C, gravitation matrix G, and joint variables q:

Find $\theta_{redundant}$ to minimize the parasitic forces $\rightarrow$ $f\left(\theta_{redundant}\right)$,

$$f\left(\theta_{redundant}\right) = M\left(q\right)\ddot{q} + C\left(q, \dot{q}\right)\dot{q} + G\left(q\right).$$

Power minimization can also be achieved via optimum posture control for the HaP-7. For this purpose, a sample study was performed in a simulation environment [8]. Figure 2 shows the comparison of the selected posture's power consumption and fixed posture ($\theta_{redundant} = 0$) power consumption for a specified task. The optimal posture selection reduces the power consumption remarkably. The cost function of the problem corresponds to the minimization of the total driving torques (τ), which can be represented in terms of applied forces F and Jacobian matrix J:

Find $\theta_{redundant}\left(\theta_3\right)$ to minimize the parasitic forces $\rightarrow f\left(\theta_3\right) = \left|\tau_1 + \tau_2 + \ldots + \tau_7\right|$.

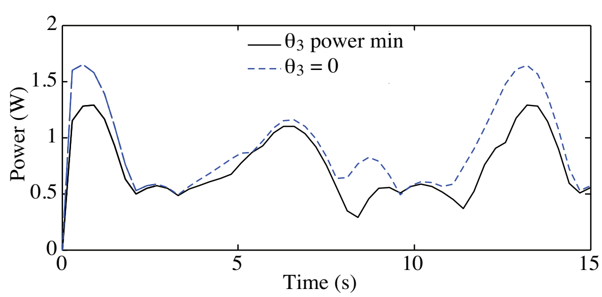


Figure 2. The comparison of the selected posture and fixed posture power consumptions.

4. Kinematic and singularity analysis

The position and orientation of the manipulator are represented by a set of equations in the forward kinematic analysis. The exponential rotation matrices are used to derive the kinematic equations in this study. It enables the representation of the equations in simple and compact form [9]. The orientation transformation matrix and the position of the haptic handle can be derived as follows:

$$\hat{C}^{(0,7)} = e^{\tilde{u}_3\theta_1} e^{\tilde{u}_2\theta_2} e^{\tilde{u}_3\theta_3} e^{\tilde{u}_2\theta_4} e^{\tilde{u}_3\theta_5} e^{\tilde{u}_2\theta_6} e^{\tilde{u}_3\theta_7}, \tag{1}$$

$$\bar{r} = d_3 e^{\tilde{u}_3\theta_1} e^{\tilde{u}_2\theta_2} \bar{u}_3 + d_4 e^{\tilde{u}_3\theta_1} e^{\tilde{u}_2\theta_2} e^{\tilde{u}_3\theta_3} e^{\tilde{u}_2\theta_4} \bar{u}_3. \tag{2}$$

Inverse kinematic solutions are indispensable for forwarding the end effector to any desired position and determining the singular configurations. It is possible to derive the inverse kinematic equations using analytical and semianalytical methods for a 6-DOF manipulator [10]. The inverse kinematic of the redundant manipulator has infinitely many solutions. In order to find the inverse kinematic solutions for this type of manipulator, one of the joint variables can be defined and the other variables can be solved in terms of the defined variable. The fourth joint variable (θ_4) of the HaP-7 can be solved analytically without using the other variables and it can be used to find other variables. The inverse kinematic solutions based on defined joint variable θ_3 and singular configurations of the HaP-7 can be derived as follows:

$$\theta_4 = \sigma \cos^{-1} \frac{x^2 + y^2 + z^2 - d_3^2 - d_4^2}{2d_3 d_4} \sigma = \mp 1. \tag{3}$$

Inverse kinematic solution based on the defined joint variable θ_3 :

$$\theta_1 = atan_2 \left[2t_1, 1 - t_1^2\right], \tag{4}$$

$$\theta_2 = atan_2 \left[\eta_2, \xi_2\right], \tag{5}$$

where, t_1, η_2, ξ_2 (*s: sine, c: cosine*):

$$t_1 = \frac{x + \sqrt{x^2 + y^2 - (s\theta_3 s\theta_4 d_4)^2}}{s\theta_3 s\theta_4 d_4 + y},$$

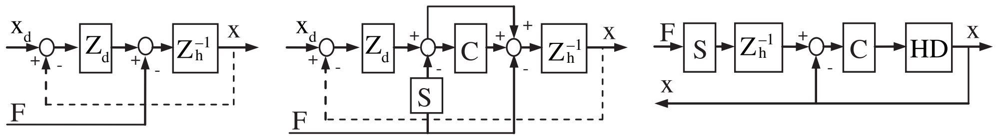
$$\eta_2 = \frac{-zc\theta_3 s\theta_3 d_4 + (c\theta_1 x + s\theta_1 y)(d_3 + d_4 c\theta_4)}{x^2 c_{\theta_1}^2 + y^2 s_{\theta_1}^2 + 2xys\theta_1 c\theta_1 + z^2}, \xi_2 = \frac{(c\theta_1 x + s\theta_1 y) c\theta_3 s\theta_3 d_4 + z(d_3 + d_4 c\theta_4)}{x^2 c_{\theta_1}^2 + y^2 s_{\theta_1}^2 + 2xys\theta_1 c\theta_1 + z^2}.$$

The inverse kinematic equations do not give any solutions in singular configurations. These are:

1. Sing. $\rightarrow \theta_2 = 0, \pm\pi$; ***2. Sing.*** $\rightarrow \theta_4 = 0, \pm\pi$; ***3. Sing.*** $\rightarrow$ x = y = 0, ***4. Sing.*** $\rightarrow \theta_6 = 0, \pm\pi$.

5. Force feedback control of the HaP-7 and VR interface

There are 2 basic control algorithms in haptic devices: impedance and admittance [11]. In the impedance type of control, the user's hand motion is sensed and a reference force is computed based on the motion and virtual model. The computed reference is sent to actuator drivers and is called the open loop impedance control (OLIC). This type of control strategy can be improved using a force feedback loop by means of a force transducer, which is called the closed loop impedance control (CLIC). It enables the virtual environment to be sensed more accurately. In the admittance control (AC) algorithm, the motion is controlled to reflect the desired force. A reference motion is computed based on the user's force and virtual model and sent to the actuator drivers. The AC algorithm requires a force transducer. The appropriate control algorithm can be selected based on the virtual environment and the device itself. The block diagram of the control algorithm types are shown in Figure 3 (x: motion, F: force, S: sensor, C: controller, Z_d: virtual model impedance, Z_h: haptic device impedance, Z_d^{-1}: virtual model admittance, Z_h^{-1}: haptic device admittance, HD: haptic device).

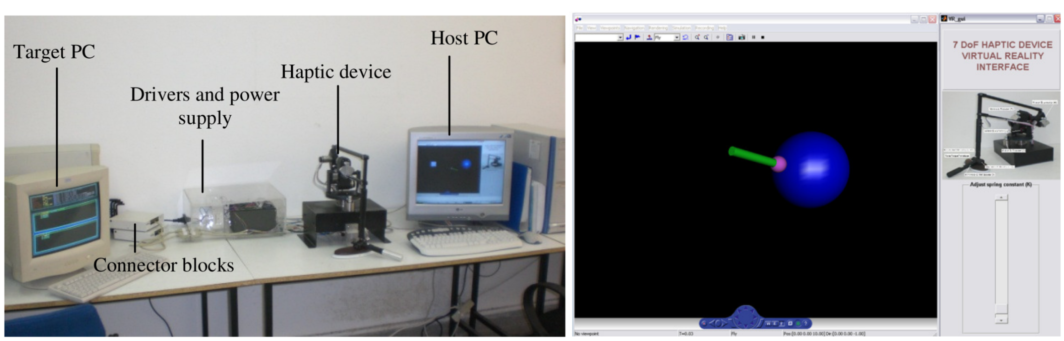


(a) (b) (c)

Figure 3. OLIC (a), CLIC (b), and AC (c) algorithms.

Figure 4 shows the experimental setup of the HaP-7 in the development of the control strategies. There are 2 computers in the setup. One of them is the host PC, devoted to developing the algorithms in MATLAB, and the other is the target PC, devoted to the control of the device. The applications running on the target PC are modeled using MATLAB/Simulink and the xPC Target® libraries on the host PC, which are sent to the target PC via a LAN connection. The virtual environments are modeled using the VRML language and they are simulated using the 3D-Animation Toolbox on the host PC.

The embedded control model in the target PC performs the manipulation of the motion/torque signals of the sensors and the computation of the reference analog voltage to the drivers. An OLIC algorithm is used for the implementation of the HaP-7 in this study. It receives the position information from the encoders and estimates the velocity and acceleration, and it computes the reference torque based on the virtual model, consisting of masses, springs, and dampers. The analog voltage corresponding to the reference torque is applied to the motor drivers. Thus, the virtual environment is sensed by the user. The motion information and motor torque reference outputs of the HaP-7 are updated at 1 kHz in the applications.

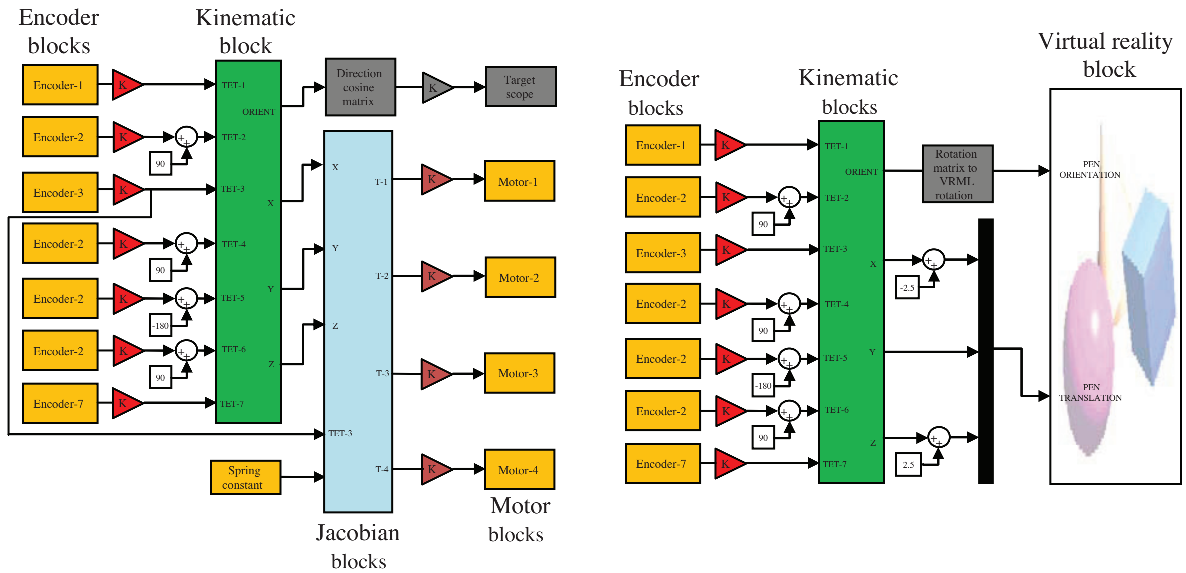


(a) (b) (c)

Figure 4. Experimental setup (a), VR interface of the HaP-7 (b), and graphical user interface (c).

The VR interface of the HaP-7 was developed in the MATLAB/Simulink 3D-Animation Toolbox (Figure 3). An elastic sphere is considered in the applications. It is modeled as a spring cluster coming up to the surface from the center. The user senses the force feedback at a perpendicular direction of the surface when the handle is pushed into the sphere. The sensed force depends on the spring coefficient and deflection of the springs. A graphical user interface was developed for the HaP-7, which enables the user to adjust the stiffness of the model using a slider bar (Figure 4). In this implementation, the HaP-7 is considered as an ideal device and its dynamic nature and electronic driver effects are ignored.

The MATLAB/Simulink models for the force feedback and visual feedback are composed of 2 models (Figure 5). The motion information of the handle to be used for the VR interface is manipulated with the signal names from the force feedback model to the visual feedback model. Thus, the VR implementation of the HaP-7 is run on 2 MATLAB/Simulink models. One of the motors of the device is locked and the device is considered as a 6-DOF manipulator in the experiments.



(a) (b)

Figure 5. MATLAB/Simulink models of the force feedback (a) and visual feedback (b).

6. Conclusion

In this study, a redundant HaP-7 design is presented and the superiority of the design is put forward. A sample VR interface was developed in the MATLAB/Simulink 3D-Animation Toolbox. The design of the device was performed by considering the maximum workspace, maximum force and torque, maximum rigidity, minimum backlash, and minimum apparent mass. The device has 20% extra workspace without compromising the other design parameters compared to similar 6-DOF designs with the same effective link lengths. The OLIC strategy was used in the implementations. As a future work, the CLIC strategies will be applied and the performance of the device will be improved by implementing the optimal posture selection methodology using the redundancy of the device.

References

[1] Merriam-Webster's Ninth New Collegiate Dictionary, Springfield, MA, USA, Merriam-Webster, 1985.

[2] D.T. Burns, Design of a Six Degrees of Freedom Haptic Device, MSc thesis, Northwestern University, Evanston, IL, USA, 1996.

[3] G.C. Burdea, Force and Touch Feedback for Virtual Reality, New York, Wiley, 1996.

[4] Ö. Başer, Haptic Device Design, MSc thesis, Middle East Technical University, Ankara, 2006.

[5] Ö. Başer, E.İ. Konukseven, "7 DOF haptic device design", Eurohaptics 2006 Conference, pp. 507–512, 2006.

[6] J. Werkmeister, A. Slocum, "Theoretical and experimental determination of capstan drive stiffness", Precision Engineering, Vol. 31, pp. 55–67, 2007.

[7] S.T. McJunkin, Transparency Improvement for Haptic Interfaces, PhD thesis, Rice University, Houston, TX, USA, 2007.

[8] Ö. Başer, E.İ. Konukseven, T. Balkan, "Optimal posture control for a 7 DOF haptic device based on power minimization", Proceedings of the 6th International Conference on Haptics: Perception, Devices and Scenarios, pp. 555–560, 2008.

[9] M.K. Özgören, "Application of exponential rotation matrices to the kinematics analysis of manipulators", 7th World Congress on the Theory of Machines and Mechanisms, 1987.

[10] M.K. Özgören, "Topological analysis of 6-joint serial manipulators and their inverse kinematics solutions", Mechanism and Machine Theory, Vol. 37, pp. 511–547, 2002.

[11] C.R. Carignan, K.R. Cleary, "Closed-loop force control for haptic simulation of virtual environments", Haptics-e, Vol. 1, 2000.