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Research Note

Simulation in virtual reality: Robotic training and surgical applications

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Abstract. Two case studies are considered in this study: one with a 4-dof robotic system and the other with a 6-dof industrial robot arm. Both robot arms have been actually operational in Mechatronics Laboratory, Gaziantep University. Different motion trajectories were designed and implemented for training, medical tasks, and surgical operations base. Simulations were carried out by using VR Toolbox in Matlab®. Virtual reality environment was developed through Simulink with real-time examples. The motions and trajectories necessary for training and surgical applications were directly observed, enabling the training of surgeons with many benefits such as reduction of the training time period through greater control during tasks and the possibility of error-free tasks.

1. Introduction

In recent years, haptic feedback in robot-assisted surgery and bilateral telemanipulation have been applied. Robotic surgical systems, telerobotics, and virtual fixtures are required to assist a surgeon. Medical simulators or surgical systems based on virtual reality require software engineering, robotics, mechatronic engineering, and microtechnology. Efficient interaction is performed in real-time using senses and skills. Virtual reality can be performed with visualization platforms such as computer monitors, head-mounted displays, and large-screen projection systems. Virtual training of medical students provides patients with safety and an increase in operating room performance. Apprenticeship is vital for surgical operations. The students must spend a great amount of time for qualified training. Different virtual tasks can be assigned to the sensorimotor functions. Surgical training is very expensive. Therefore, reliable training is possible with VR technology and used as supplementary training materials with a great promise [1]. The virtual reality is introduced by surgeons to ensure reliable training by improving their surgical skills. Repeated trainings can be performed with no harm to a patient. Simulators can train nurses, medical students, etc. while offering no need for supervision. Therefore, a platform is provided that causes no harm to a patient. Repeated training can be easily performed. Virtual Reality (VR) based systems have been at play since early 1980s. Different studies have been conducted in this regard since then, some of which are included here to show their importance in medical training [2].

Khor et al. [3] carried out a study on Augmented Reality (AR) and Virtual Reality (VR) for the use of digital surgical environment. In surgical health care, anatomical evaluation, broadcasting and recording surgery, telementoring and education, operational and patient-wise benefits are considered that are of course

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subject to limitations. Al-Mashhadany [4] studied Scara robot by modeling and simulating the virtual reality model. Buckley et al. [5] showed that surgical skills, hand-eye coordination, intuitive movements, and the ability to work with images could be improved by simulators. Therefore, a surgeon can be trained in the operation theatre by providing a safe environment for him/her. Nooshabadi et al. [6] achieved an effective surgical training system to simulate tool-tissue system by a meshless method. Almusawi et al. [7] performed a simulation study of a robotic arm (4 degrees of freedom) with Virtual Reality Model (VRM). Then, Almusawi [8] performed a study on haptic teaching and virtual reality on thoracoscopic surgery in his thesis. Later, Almusawi et al. [9] combined the aforementioned ideas using neural networks.

The purpose of this study is to show the interface between an operator and the robotic arm in the virtual world. The paper is structured by 4 sections. Robotic systems are given in Section 2 with Matlab® robotic toolbox. Virtual Reality Models for OWI-535 and Denso robot arm are given in Section 3. Conclusions are included in Section 4.

2. Description of robotic systems

Two robotic systems are presented here. OWI-535 robot arm is an articulated manipulator for performing pick-and-place in a laboratory environment. This system is built at Gaziantep University, Mechatronics Laboratory. This arm has four revolute joints with three links and a gripper. All joints are actuated by five small DC motors; to be specific, the base is of 270° rotation, a shoulder is of 180°, an elbow's range is 300°, a wrist is of 120°, and the gripper is 1.7 inches open [10]. OWI-535 robot is shown in Figure 1. Some modifications are applied to OWI-535 robot arm to respond to possible requirements during the tests in the laboratory by integrating angular position sensors with each joint. A computer interface system is designed to drive 5 DC motors using the angular joint positions on PC. The interface system is introduced as a microcontroller board with a USB connection. Control software is designed by Matlab® GUIDE next, D-H model execution, forward and inverse kinematics, control, and trajectory generation [11,12].

Denso 6-axis robot system is a 6-DOF robotic arm. The Denso robot arm has six encoders that measure the angular position of the six motors. The overall arm length is 420 mm, the Payload is 2 kg, and position axes with repeatability in each of X, Y, and Z directions are equal to ± 0.02 mm. The position detectors are absolute encoders; Denso robot weight is approximately 14 kg. The controller is quanser custom ethernet-based. The maximum composite speed is 3900 mm/s. Figure 2 shows the world coordinate frame and the joint coordinate frames to define the kinematics, inverse kinematics, and Jacobian matrix [12].

Figure 1. Robotic systems.

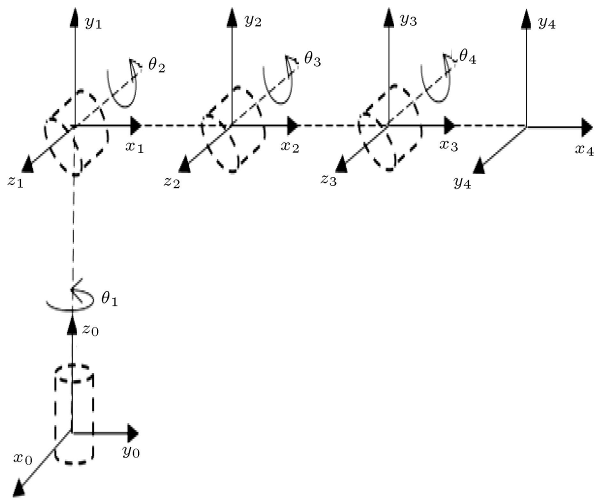


Figure 2. Coordinate frames of the OWI-535 robotic arm links.

2.1. Coordinate representations

The robot manipulator OWI-535 has four links. The coordinate frames of each link are shown in Figure 2. A homogeneous transformation matrix, T_4^0, is expressed as the position and orientation of the robot.

$$T_4^0 = \begin{bmatrix} R_4^0 & O_4^0 \\ 0 & 1 \end{bmatrix}, \tag{1}$$

where R_4^0 is the rotation matrix (3×3), O_4^0 is the position vector of the end-effector in the base frame, and the Denavite Hartenberg (D-H) for each link homogeneous transformation, A_i, is represented as a product of four basic transformations [13]. The homogeneous transformation matrix for the four-axe robot is T_4^0. D-H parameters for the links are shown in Table 1.

$$A_i = \mathrm{Rot}_{z,\theta_i}\mathrm{Trans}_{z,d_i}\mathrm{Trans}_{x,a_i}\mathrm{Rot}_{x,a_i}, \tag{2}$$

$$T_4^0 = A_1A_2A_3A_4. \tag{3}$$

The relationship between the joint angles and the position and orientation of its end effector is described by kinematics [11]. Denso robot kinematics is required for teaching control method with the transformation matrices that control the system. The Denso robotic system is a six-DOF serial link with 6 revolute joints. The kinematics analysis is done following the performance of the system coordinate frame. The coordinate O_0, X_0, Y_0, and Z_0 is fixed to the base, which is the base frame. The other coordinate frames are attached to the corresponding links. The reference coordinate frame is shown in Figure 3.

The homogeneous transformation matrix represents the position and orientation of the end effector with respect to the base coordinate; T_6^0 is then given for the overall system.

$$T_6^0 = \begin{bmatrix} R_6^0 & P_6^0 \\ 0 & 1 \end{bmatrix}, \tag{4}$$

where R_6^0 is the rotation matrix 3×3, and P_6^0 is the position vector of the end-effector in the base frame coordinate. Forward and inverse kinematics are created to create a relationship between the joint angles and the position and orientation of the end effector; in addition, the Denavite Hardenberg (D-H) is again used to analyze DENSO robot. The single-link homogenous transformation matrix, A_i, is as follows:

Table 1. D-H parameters of links (OWI-535).

Link no.	θ	D (cm)	a (cm)	α
1	θ_1	7	0	$\pi/2$
2	θ_2	0	9	0
3	θ_3	0	11.2	0
4	θ_4	0	11.2	0

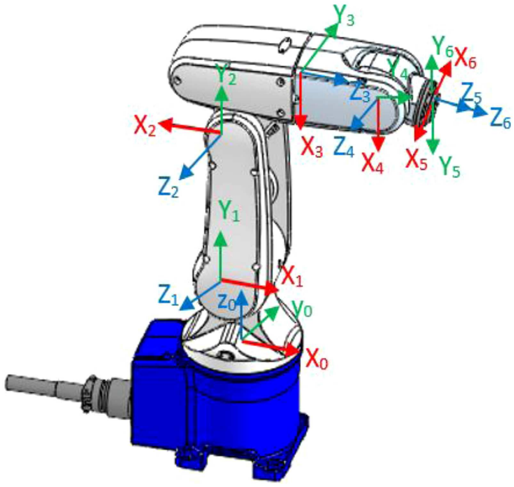


Figure 3. Reference coordinate frame for the Denso robot system.

$$A_i = \mathrm{Rot}_{z,\theta i}\mathrm{Trans}_{x,di}\mathrm{Trans}_{x,\alpha i}\mathrm{Rot}_{x,\alpha i}, \tag{5}$$

$$A_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{6}$$

where i is the link no., θ_i is the joint rotation angle, a_i is the length of links, α_i represents the twist angles, d_i is the link offsets, and θ is the joint angles. The system has six links and a gripper. Here, i is link no., $S\theta_i = \sin\theta_i$, $C\theta_i = cos\theta_i$, θ_i is the joint rotation angle, a_i is the length of links, α_i is the twist angles, d_i is the link offsets, and θ is the joint angles. The homogeneous transformation matrix is calculated by the multiplication of matrices in Eq. (7):

$$T_6^0 = A_1A_2A_3A_4A_5A_6A_{\text{gripper}}. \tag{7}$$

A_{gripper} is the transformation matrix of the gripper. The joint angles and the gripper transformation matrix are given to calculate the position and orientation of gripper's finger. Table 2 gives D-H parameters of the Denso robot.

Table 2. D-H parameters of the Denso robot.

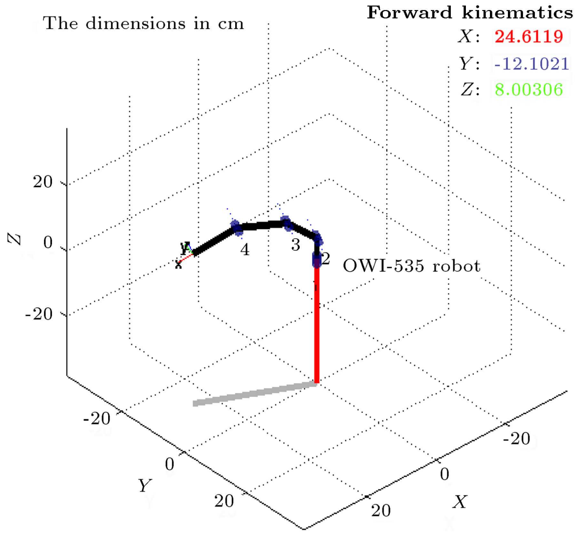
Link no	θ_i	d_i (mm)	a_i (mm)	α_i
1	q_1	125	0	$\pi/2$
2	q_2	0	210	0
3	q_3	0	-75	$-\pi/2$
4	q_4	210	0	$\pi/2$
5	q_5	0	0	$-\pi/2$
6	q_6	70	0	0

2.2. Kinematics using Matlab® robotic toolbox

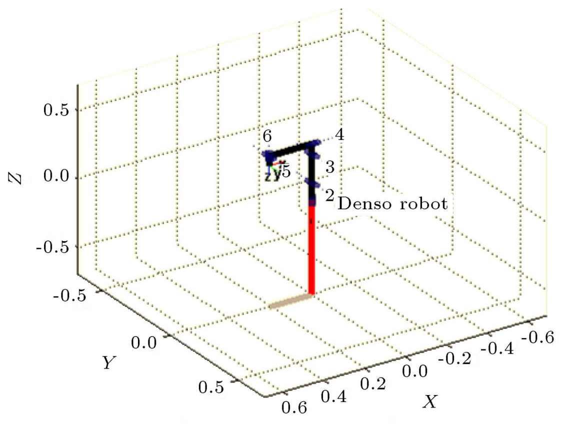
Robotic toolbox includes many functions to simulate robotic arms. Forward and inverse kinematics, forward and inverse dynamics, and trajectory generation are performed. Trajectories are designed through training and surgical operations. In this study, the toolbox is used for OWI-535 and Denso robotic arm [11]. The dynamic equation of the robot is generated by the Euler-Lagrange method as follows:

$$M\left(q,\dot{q}\right)\ddot{q}+C\left(q,\dot{q}\right)\dot{q}+G(q)=\tau-B\dot{q}, \qquad (8)$$

where $M(q,\dot{q})$ is the mass and inertia matrix with n degree of freedom; $C(q,\dot{q})$ is the matrix with centripetal and Coriolis effects; $G(q)$ is the vector of gravitational torques and forces; τ represents the joint torques and forces; and $(q,\dot{q},\ddot{q})$ are the joint positions, velocities, and accelerations. The graphical representation of OWI-535 and Denso robot is given by MATLAB using robotics toolbox, as shown in Figure 4(a) and (b).



(a)



(b)

Figure 4. Representation of robotic systems.

3. Building virtual reality model

The robot dynamics is modeled by Simulink blocks and visualized in Virtual Reality Model (VRM). Figure 5 shows Virtual Reality Model (VRM) for OWI-535 robot. The signals are transferred between Simulink model and VRM by the link rotation matrix (3×3) [13,14]. The rotation matrixes are converted to equivalent rotation axis, and the angles form Virtual Reality Modelling Language (VRML) for the orientation of bodies. The structure of virtual model is built by defining every node in a tree-object structure and, as a box node, transforming node and material node. Trajectories are synchronized with physical hardware environment of OWI-535 Robot in Mechatronics Laboratory. The arm is built and, then, modified with a card for further communication and control. A Virtual Reality Model (VRM) is also prepared. Programs are developed by Graphical User Interface (GUI). Simulink model is built for the arm. Similarly, CAD drawing is done by Solid Works for Denso robot, F/T sensor, and gripper. CAD model is connected with Simulink to

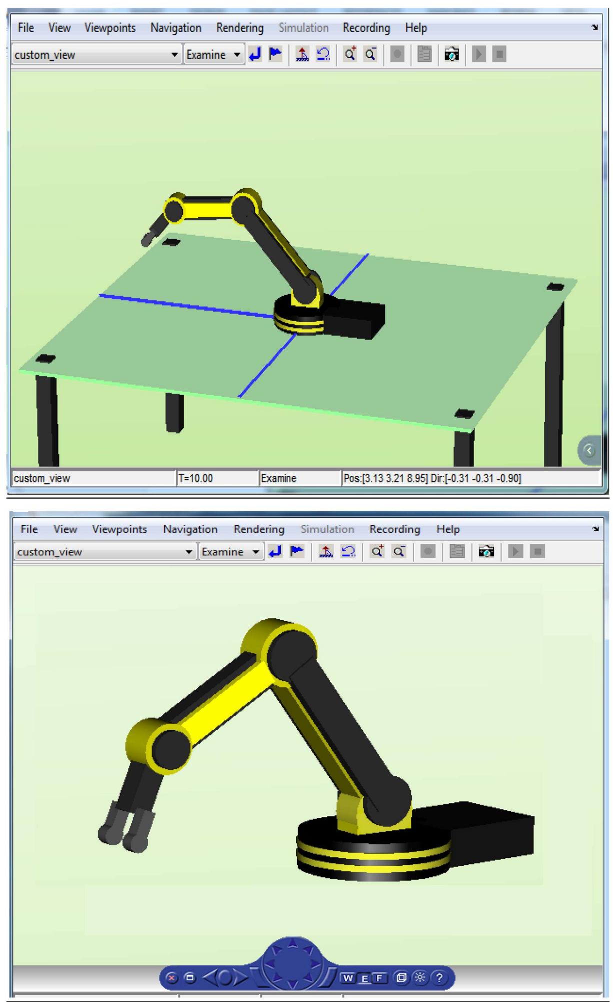


Figure 5. Robot Virtual Reality Model (RVRM) .

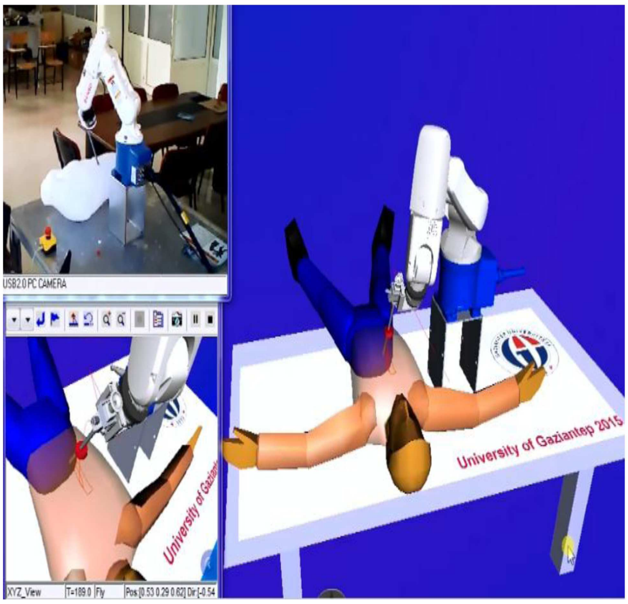


Figure 6. CAD model Denso system.

create a visualized Denso system by using Simulink 3D animation. The virtual model is used to display the teaching path and motion in real-time. Figure 6 shows CAD of Denso system and with a surgical operation.

4. Conclusion

Two robotic systems were built and used during the study. VRM of both systems was studied. OWI-535 system was built first for the initial experiments and training purposes. VRM of Denso robot was particularly used for thorascopic surgery as an example. Robotic toolbox was used for building robotic analysis. Kinematic analysis of both systems was performed with trajectories necessary during operations. Simulated human models can be used. Studies of VR continued for the purpose of rehabilitation in mechatronics laboratory. Surgical simulators and VR models will have a great role in microsurgery and nano surgery.

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Biographies

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