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A Novel Kinematic of a 4 d.o.fs Haptic Device Based on the Delta Robot Architecture

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Abstract. This paper presents a novel kinematic of haptic device with 4 d.o.f for medical use. The kinematic of the proposed device is based on delta robot architecture. The challenging task was to obtain the three orientations of the tool for each Cartesian location of the mobile platform. Gimbal joints were specifically used in this purpose. The kinematic and haptic models of the new device are presented. A 3d printed prototype was developed to validate the new kinematic and present a the first conceptual design.

Keywords: Delta robot · Haptic devices · Minimally Invasive Surgery · Teleoperation system

1 Introduction

Haptic devices refer to a system providing a “sense of touch” for a user to realize a remote or virtual reality environment. There has been an increased need for haptic devices in the fields of engineering, medicine [1, 2, 4], teleoperation, assistance and activity [3, 7]. Thus, haptic devices were designed to reproduce interaction force and torque of remote or virtual environments.

Broeren et al. developed a virtual reality environment for remedial exercises in the left hemiparetic arm to better interpret strokes of patients arms done with the haptic interface “PHANToM (Geomagic, USA)” [5]. Son et al. utilized the haptic interface “Omega.3 (force dimension, Switzerland)” for the teleoperation of unmanned aerial vehicles [6].

For Minimally Invasive Surgery, the haptic device should have at least four degrees of freedoms (d.o.fs) [4]. Three rotations around a Remote Center of Motion (RCM) and one translation. Haptic devices have different kinematics: serial, parallel and hybrid. Most of them have parallel or hybrid structure based on the delta robot. However, the delta structure is used to reproduce three translation d.o.fs. In this paper, a novel kinematic structure of four d.o.fs haptic device is proposed. This structure is based on the delta structure to generate three rotations around a RMC and one translation.

The paper is organized as follows: Sect. 2 presents an overview of the teleoperation system for the Minimally Invasive Surgery. The new kinematic of the haptic device is shown in Sect. 3. Section 4 presents the forward kinematic and the haptic models. A prototype of the new haptic device is briefly described in Sect. 5. Section 6 provides some brief concluding remarks.

2 Teleoperation Systems for Minimally Invasive Surgery

For Minimally Invasive Surgery (MIS), instruments enter the patient's body through tiny incisions (Fig. 1). This restriction limits the motion of instruments from six degrees of freedoms (d.o.fs) for classic surgery to four d.o.fs for MIS. The four d.o.fs are three rotations around the incision point and one translation within the instrument axis.

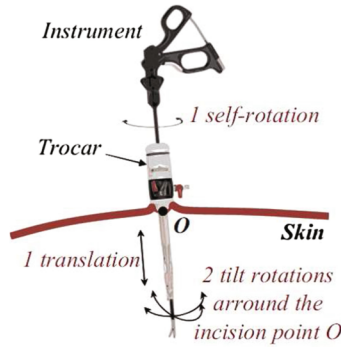


Fig. 1. Minimally Invasive Surgery motions.

MIS gestures were studied in previous work [4]. The motion of instruments were recorded, while a surgeon executes a MIS tasks, in order to identify the required workspace. This study showed that the required workspace is encompassed in a cone with an apex angle of 26° . The translation is about 112 mm and the self-rotation is between $\pm 180^\circ$.

A prototype of a surgical robot was designed with a spherical serial architecture (Fig. 2).

The geometric parameters were optimized for the required workspace. The motion control of the robot was established and validated. The robot was developed to be controlled using a master device with haptic capability. A six-axes Force/Torque sensor is installed in the surgical robot (Slave) and a master robot was designed using the spherical parallel architecture (Fig. 3).

The first prototype of the master has a major issue which is the presence of the parallel singularity inside its workspace. The parallel singularity amplifies the error when we solve the Forward Kinematic Model (FKM) of the parallel robot as well as the actuator torques required for haptic feedback.

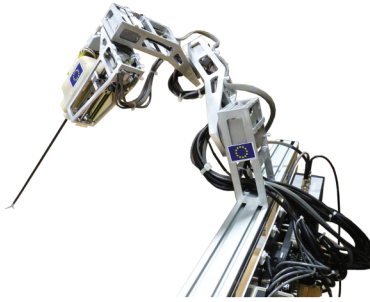


Fig. 2. MIS slave robot.



Fig. 3. The first prototype of the haptic device.

To solve the first issue related to the accuracy of the FKM, an extra sensor was installed in the moving platform [8]. This solution has eliminated the FKM error and has allowed a real-time control of the surgical robot since it speeds-up the calculation of the FKM.

For the second issue, a solution based on the actuator redundancy was proposed in [9]. This solution required the installation of a redundant actuator on the moving platform. The redundant actuator keeps the actuator torques in their limits, however, it increases the moving platform weight. For this reason, this solution is not suitable.

To cope with these drawbacks, in the next paragraph a novel kinematic architecture of the haptic device is proposed.

3 The New Kinematic of the Haptic Device

Many developed haptic devices are based on the Delta architecture. Those devices are designed to allow 3 translational d.o.fs. However, the intended

surgical task requires 3 pure rotations d.o.fs and one translation. Therefore, the challenging task is to get orientation d.o.fs from a Delta architecture.

The orientation can be simply obtained by adding a fourth leg with two spherical joints: one joint links the leg to the base and the other joint links the leg to the moving platform. In this case, the fourth leg has only orientation d.o.fs around the first spherical joint (the joint at the base). To add the translation d.o.f, a prismatic joint is added between the two spherical joints.

The new kinematic of the 4 d.o.fs haptic device is shown in Fig. 4. The spherical base joint is decoupled into a gimbal (universal) joint and a revolute joint to make possible the control of the self-rotation. The center of the gimbal joint coincides with the center of rotation (CR) of the haptic device.

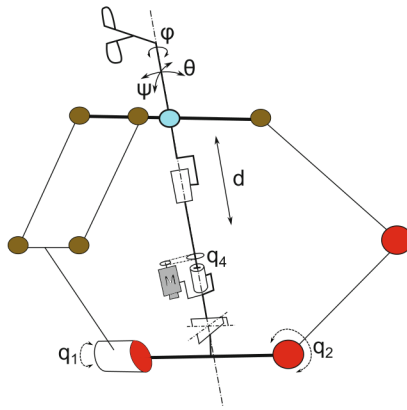


Fig. 4. Novel kinematic based on the Delta robot architecture.

The spherical joint linking the fourth leg to the moving platform is obtained by composing revolute joints like a gimbal joint, as shown in Fig. 5. This kinematic has more orientation range than a classic spherical joint.

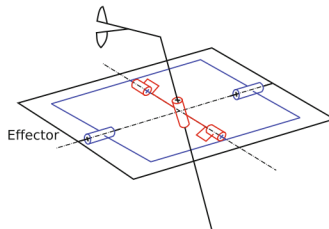


Fig. 5. Composed spherical joint.

4 Kinematic and Haptic Models of the Haptic Device

4.1 Forward Kinematic Model

The Forward Kinematic Model (FKM) gives the orientation described by the Euler ZYZ angles (ψ, θ, φ) and the translation d using the active joints (q_1, q_2, q_3, q_4) (Fig. 4). However, the FKM of the delta robot gives the position of the moving platform described by the vector $O_0z_e = [x_d, y_d, z_d]^T$ with O_0 is the center of the universal joint and z_e is the center of the spherical joint on the moving platform.

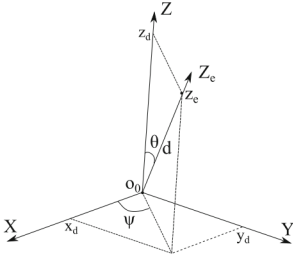


Fig. 6. Geometric parameters for the kinematic model.

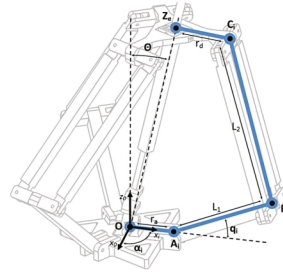


Fig. 7. Geometric parameters for Delta model

Figure 6 shows the geometric parameters describing the moving platform in the Cartesian frame.

The moving platform can be described on the first side using Euler angles in the Cartesian frame as follows:

$$O_0z_e = d \cdot R_z(\psi) \cdot R_y(\theta) \cdot Z = d \cdot \begin{bmatrix} -\cos\psi \sin\theta \\ -\sin\psi \sin\theta \\ \cos\theta \end{bmatrix} = \begin{bmatrix} x_d \\ y_d \\ z_d \end{bmatrix} \quad (1)$$

The translation d is equal to:

$$d = \| o_0z_e \| = \sqrt{x_d^2 + y_d^2 + z_d^2} \quad (2)$$

The Euler angle θ and ψ are equal to:

$$\theta = \text{acos}\left(\frac{z_d}{d}\right) \quad (3)$$

$$\psi = \text{atan2}\left(-\frac{y_d}{d \sin\theta}, -\frac{x_d}{d \sin\theta}\right) \quad (4)$$

The self-rotation φ is given directly by q_4 .

On the other side, the moving platform can be described using the Delta FKM with geometric parameters shown on Fig. 7:

$$(x_d - x_i)^2 + (y_d - y_i)^2 + (z_d - z_i)^2 = L_2^2 \tag{5}$$

Where,

$$\begin{cases} x_i = r + L_1 \cos(q_i) \\ y_i = r + L_1 \cos(q_i) \\ z_i = -L_1 \sin(q_i) \end{cases} \quad \text{with } r = r_a - r_d \tag{6}$$

The solution of Delta FKM model is given by the solution of those three equations, one for each leg of the Delta ($i = 1, 2, 3$).

Those two models combined gives us the FKM model of the new haptic device.

4.2 Haptic Model

The haptic control model relates the actuator torques, τ , with respect to the moving-platform Force/Torque, T . However, the delta structure can apply only Force, F . From the Fig. 8, a relation between F and T can be established.

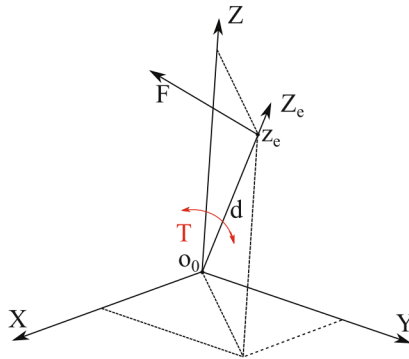


Fig. 8. Force/Torque control.

This relation is as follows:

$$T = O_0 z_e \times F \tag{7}$$

The actuator torques, τ , can be determined using the following static relation:

$$\tau = J^T F + \tau_s \tag{8}$$

with J is the Jacobian matrix of the delta structure and τ_s is the gravity compensation torque vector.

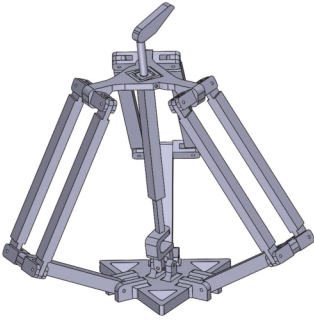


Fig. 9. CAD model of the new kinematic.

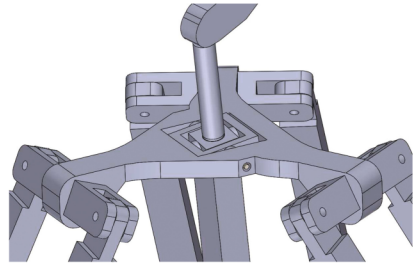


Fig. 10. Composed spherical joint.

5 Prototype of the New Haptic Device

The CAD model of the new kinematic 4 d.o.fs haptic device is shown in Fig. 9. The CAD model validates the new kinematic. The spherical joint decoupled into a gimbal joint and a revolute joint is shown in Fig. 10.

A 3D printed prototype was developed (Fig. 11). This prototype was made to validate the new kinematic of the master device. The moving platform can be simply manipulated in the four d.o.fs.



Fig. 11. 3D printed prototype.

6 Conclusions

In this paper, a novel kinematic structure of a haptic device dedicated for teleoperation systems is presented. The proposed kinematic is based on the delta

robot architecture. The kinematic and the haptic models were presented in the paper. The kinematic of the novel device is validated by a 3D printed prototype. In future works, the geometric parameters of the haptic device will be optimized based on the needed workspace for the medical application of MIS. A new prototype of the haptic device will be developed and used to control a surgical slave robot.

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