4haptic : A dexterous 4 d.o.fs haptic device based on Delta architecture

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Abstract. This paper introduces a novel kinematic of 4 d.o.fs haptic device based on Delta architecture. A fourth leg is added to the Delta structure to convert translations into rotations and translation of the handle. The fourth leg is linked to the base and the moving platform by two spherical joints. The kinematic model of the new structure, called 4haptic, is presented. The novel device has a better dexterity distribution compared with previous developped master device based on spherical parallel manipulator architecture. The 4haptic device offers a singularity free useful workspace which makes it a suitable candidate to perform tele-operated Minimally Invasive surgery.

Key words: Delta robot, Haptic devices, Minimally Invasive surgery, Teleoperation system

1 Introduction

Haptic devices are developed to simulate interaction feeling between the user and a virtual environment, by applying force and torque feedback on a master device. Such devices are widely used in virtual reality [1], gaming [2] and tele-robotics [3]. In medicine, haptic devices are used for training in virtual environment to enhance the practice of surgical techniques [4, 5] or for tele-operation [6, 7].

A previous study [8] highlights that Minimally Invasive Surgery (MIS) gesture requires at least four degrees of freedom (d.o.fs) to perform a suture. Therefore, the haptic controller should have three rotations around the Remote Center of Motion (RCM) and a translation along its self rotation axis.

A previous haptic interface based on spherical parallel architecture has been developed for MIS procedure. This Spherical Parallel Manipulator (SPM) suffers from the presence of the singularity inside the useful workspace. The solution proposed is to use a Delta structure to convert three translationals d.o.fs to three rotationals and one translational d.o.fs.

This paper focuses on the kinematic model and the kinematic performances of this new interface based on Delta structure called 4haptic since it has 4 d.o.fs.

This paper is organized as follows. In Section 2, an overview of a tele-operation system for MIS is presented. The kinematic model of the new device is explained in Section 3. Section 4 compares the dexterity of the new interface to the previous one. Section 5 concludes this paper.

2 Gesture in Minimally Invasive Surgery and Teleoperation

The main goal of tele-surgery is not to develop an autonomous system but to assist the surgeon during his task by adding accuracy, safety and comfort. Teleoperation systems consist of a slave surgery robot controlled by a master interface (with or without haptic feedback).

Minimally Invasive Surgery uses instruments inserted into patient's body through tiny incisions points. Unlike open surgery which generally requires up to six d.o.fs, minimally invasive procedure requires only four d.o.fs : three rotation around incision point and one translation along the instrument axis (Fig. 1). This is due to the constrain imposed by the trocar.

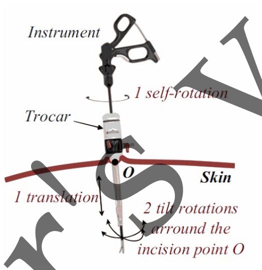

Fig. 1 Minimaly Invasive Surgery Motions

A previous study of MIS gesture using a motion capture system has reveal the useful workspace needed by a surgeon to perform arterial anastomosis [8]. Using those results a slave robot (Fig. 2) was designed and optimized to perform MIS tasks. To describe the useful workspace, the slave robot was design with a serial spherical architecture.

To implement haptic feedback on the master interface, a six-axis force sensor has been inserted between the effector and the slave robot.

A master interface (see Fig. 3) has been designed based on a spherical parallel architecture. Multiple prototypes of that interface have been developed. The first prototypes (see Fig. 3) suffers from the presence of parallel singularity in its workspace. This singularity is located in the center of useful workspace and depends on the self rotation of the moving platform. It induces errors during Forward Kinematic Model (FKM) evaluation and requires high motor torques for haptic feedback [9]. Due to

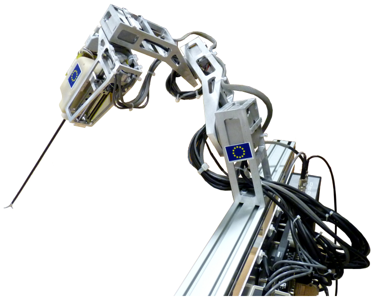

Fig. 2 MIS slave robot

Fig. 3 1st prototype of master interface

that singularity and a lack of dexterity, the first prototype doesn't allows us to properly control the slave robot.

To reduce effects of the singularity on haptic feedback, a redundant actuator has placed on the moving platform [10]. This setup allows to obtain the needed torques for haptic feedback, however it increases the weight of the moving platform. The interface is not transparent anymore, it's not a suitable solution to control the slave robot.

A novel kinematic architecture based on Delta structure is proposed in this work in order to cope with those drawback.

3 4haptic Device Architecture

3.1 A New Kinematic Structure

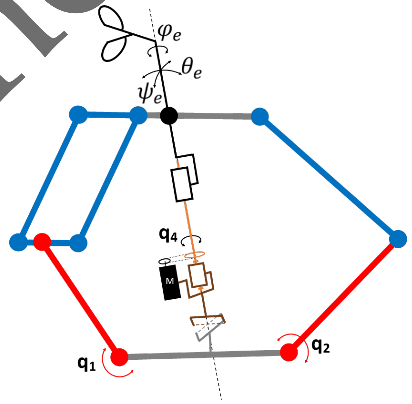

Fig. 4 New Kinematic based on Delta robot architecture

The intended MIS procedure requires three rotational and one translational d.o.fs. However, classical Delta device allows three translational d.o.fs. To convert translation into rotations, a fourth leg is added to the structure. This extensible leg is linked thanks to two spherical joints on the base and the moving platform. The three rotational d.o.fs are given by the orientation of the fourth leg with respect to the base. The translational d.o.fs is given by a prismatic joint located in the fourth leg as shown in figure 4.

The spherical joint on the base is composed of an universal joint and a revolute joint which allows to control self-rotation φ_e.

A CAD model and a 3D printed prototype have been designed to validate the kinematic.

3.2 Forward Kinematic Model

To evaluate the position of the moving platform, we have to determine the coordinates of vector $\mathbf{OD} = [x_d, y_d, z_d]$ in R_0 where O is the origin of the fixed frame attached to the base of the Delta and D is the center of the moving platform.

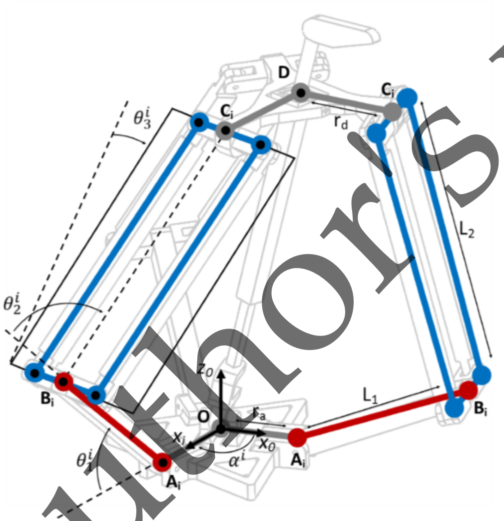

Fig. 5 Geometric parameters of Delta robot

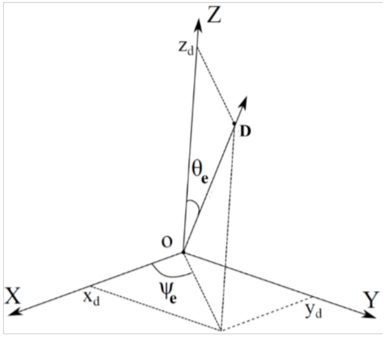

Fig. 6 Orientations of the 4th leg (vector **OD**)

The geometric parameters of Delta structure are L_1, L_2, r_a, r_d and α^i as described in the figure 5. θ_1^i defines the active joint angle and θ_2^i, θ_3^i the passive joint angles of each leg. The coordinate of the moving platform (point D) are given by the forward kinematic model written as follows for each leg of the Delta:

$$\begin{cases} x_d = C\alpha^i(r + L_1 C\theta_1^i + L_2 C\theta_3^i C\theta_{12}^i) - L_1 S\alpha^i S\theta_3^i \\ y_d = S\alpha^i(r + L_1 C\theta_1^i + L_2 C\theta_3^i C\theta_{12}^i) + L_1 C\alpha^i S\theta_3^i \\ z_d = L_1 S\theta_1^i + L_2 C\theta_3^i S\theta_{12}^i \end{cases} \quad for \quad i = 1,2,3 \tag{1}$$

$$with \quad r = r_a - r_d \quad and \quad C\Theta = Cos(\Theta); S\Theta = Sin(\Theta); C\Theta_{12} = Cos(\Theta_1 + \Theta_2)$$

The forward model determines the position $x_{d,} y_{d,} z_d$ of the moving platform for any given configuration of actuated revolute joints θ_1^i. The position of point D is given by solving these three equations (for $i = 1,2,3$):

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

$$where \quad \begin{cases} x_i = cos(\alpha^i)(r + L_1 cos(\theta_1^i)) \\ y_i = sin(\alpha^i)(r + L_1 cos(\theta_1^i)) \\ z_i = -L_1 sin(\theta_1^i) \end{cases} \tag{3}$$

The orientation of the handle created by the fourth leg and the two spherical joints is described using Euler ZYZ angles $(\psi_e, \theta_e, \varphi_e)$. A fourth active joint θ_4 is introduce to control the self-rotation (φ_e).

One can describe the coordinates of vector OD using $\psi_e, \theta_e, \varphi_e$ and L_d as follows (see Fig. 6):

$$\mathbf{OD} = L_d \cdot R_z(\psi_e) \cdot R_y(\theta_e) \cdot Z = L_d \cdot \begin{bmatrix} cos\psi_e sin\theta_e \\ sin\psi_e sin\theta_e \\ cos\theta_e \end{bmatrix} = \begin{bmatrix} x_d \\ y_d \\ z_d \end{bmatrix} \tag{4}$$

$$\begin{cases} L_d = \parallel OD \parallel = \sqrt{x_d^2 + y_d^2 + z_d^2} \\ \theta_e = a\cos(\frac{z_d}{L_d}) \\ \psi_e = a\tan 2(-\frac{y_d}{L_d \sin\theta_e}, -\frac{x_d}{L_d \sin\theta_e}) \\ \varphi_e = \theta_4 \end{cases} \tag{5}$$

The self rotation φ_e is directly given by the fourth active jointθ_4.

Those two models combined gives the FKM model of the 4haptic interface using $\theta_1^1, \theta_1^2, \theta_1^3, \theta_4$ as input to evaluate $\theta_e, \psi_e, \varphi_e$ and L_d.

4 Dexterity Analysis and Comparison between SPM and 4haptic devices

Kinematic perfomances evaluate the ability of moving and applying forces to the handle. In order to measure the kinematic performances we use dexterity criteria. The dexterity describes the amplification of the errors due to the kinematic and static transformations between Cartesian and joints spaces. The dexterity is evaluated using the Condition number of Jacobian matrix $\kappa(J)$ that describe the kinematic of the master device [11].

The dexterity is evaluated as follows :

$$\eta(J) = \frac{1}{\kappa(J)} \quad where \quad \kappa(J) = ||J||\,.\,\left|\left|J^{-1}\right|\right| \tag{6}$$

4.1 SPM Dexterity

The Spherical Parallel Manipulator (SPM) dexterity has been evaluated in previous work [9, 10]. On that architecture, the distribution of dexterity depends on self rotation φ.

For MIS procedure, the center of the workspace is the most important region. According to the previous study on that interface [9], for $\varphi = 0°$, the dexterity is maximum on the center of the workspace but still low (about 0.4, see Fig. 7), however for $\varphi = 50°$, the dexterity on the center of the workspace vanishes (see Fig. 8). The presence of this singularity in the workspace amplifies the error during FKM evaluation and requires high motor torque for haptic feedback. Due to this singularity, the self-rotation is not controllable anymore when the dexterity is too low.

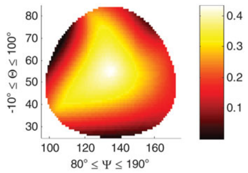

Fig. 7 Dexterity distribution for $\varphi = 0°$

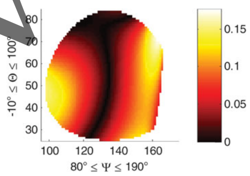

Fig. 8 Dexterity distribution for $\varphi = 50°$

A solution with a redundant actuator installed on a joint of the platform has been studied [10]. This modification of the device improves the dexterity of the interface (up to 0.5), however it increases the weight of the moving platform. For that reason, the solution is not suitable.

4.2 4haptic Dexterity

By differentiating equation (2), the Jacobian matrix of the 4haptic device can be obtained. The fourth d.o.f. (self rotation φ_e) is excluded from the study since this rotation is totally decoupled from the rest of the system.

$$\dot{x_d}(x_d - x_i) + \dot{y_d}(y_d - y_i) + \dot{z_d}(z_d - z_i) = \dot{x_i}(x_d - x_i) + \dot{y_i}(y_d - y_i) + \dot{z_i}(z_d - z_i) \tag{7}$$

This equation can be written as follows:

$$J_\upsilon v_d = J_\theta \dot{q} \tag{8}$$

Where $v_d = [\dot{x_d}, \dot{y_d}, \dot{z_d}]^T$ (platform velocity) and $\dot{q} = [\dot{\theta}_1^1, \dot{\theta}_1^3, \dot{\theta}_1^3]^T$ (joints velocities)

$$J_\upsilon = \begin{bmatrix} x_d - x_1 & y_d - y_1 & z_d - z_1 \\ x_d - x_2 & y_d - y_2 & z_d - z_2 \\ x_d - x_3 & y_d - y_3 & z_d - z_3 \end{bmatrix} \quad J_\theta = \begin{bmatrix} J_1 & & \\ & J_2 & \\ & & J_3 \end{bmatrix} \tag{9}$$

with

$$J_i = -L_1 C\alpha^i S\theta_1^i (x_d - x_i) - L_1 S\alpha^i S\theta_1^i (y_d - y_i) - L_1 c\theta_1^i (z_d - z_i) \quad for \quad i = 1,2,3 \tag{10}$$

The global Jacobian matrix used to evaluate dexterity is defined by $J = (J_\upsilon)^{-1} J_\theta$.

The dexterity of the new interface has been evaluated (Fig. 9) using different fixed values of the fourth leg length L_d, which correspond to the fourth joint parameter.

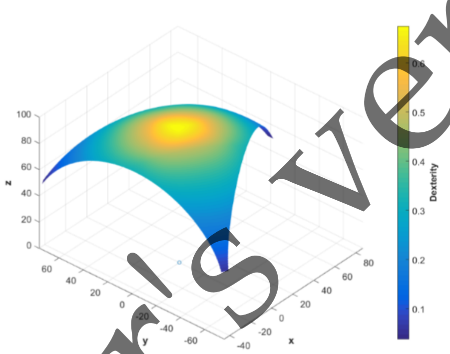

Fig. 9 Dexterity distribution of the 4haptic device in Cartesian space for $L_d = 100mm$

The new haptic interface has a maximum dexterity of 0.7. This value is greater than the one obtained for previous SPM [9], which was limited to 0.4.The dexterity is maximum in the center of workspace. Unlike SPM, it doesn't depends on the self-rotation φ since this rotation is decoupled from the rest. This makes the new architecture better and suitable haptic interface for the intended surgical task.

5 Conclusion

This paper presents a novel kinematic architecture of a 4 d.o.fs haptic interface based on Delta structure, called 4haptic. The kinematic model as well as the dexterity distribution of the novel architecture has been evaluated in this paper. For the intended task, the dexterity of this device is higher than the existing haptic controller (Spherical Parallel Manipulator) [9]. In addition, the new interface has no singularity in the useful workspace. A higher dexterity and absence of singularity in the workspace will improve the force feedback of the novel device, which will be a suitable haptic interface for MIS teleoperation system. In future works, a prototype will be designed and built based on the results of this study in order to control efficiently a surgical slave robot.

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