2-Degree-of-Freedom Haptic Device for Different Medical Procedure Decision

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***Abstract*— Haptic interaction is an emerging space of research and has gained popularity as an additional feedback to enhance human experience of the environment which facilitates users to intermingle with virtual object using their haptic sensual modality. Haptics was used to enhance user experience by providing tactile feedback, hence it is a treasured tool in minimally aggressive surgical simulation and training. The extensive application of haptics includes virtual reality simulation, medical, teleportation, manufacturing, education, and rehabilitation. This work presents the design and implementation of low cost two degree of freedom haptic device envisioned different medical procedure such as skin surgical training, epidural injection, dental education training . In order to calculate force and torque kinematics of the subsequent device are deliberated and the Jacobian determined. This work briefs the modeling of two DOF haptic device including its forward kinematics, inverse kinematics, forward kinematics of velocity inverse kinematics of velocity, and calculation of device parameters such as forces, torque. The future work of this paper is to interface haptic device with various virtual model for medical simulation and training.**

Keywords—Haptic DOF, 2-DOF Device, Kinematics, Medical training.

I. INTRODUCTION

The word haptics, supposed to be plagiaristic haptikos from the Greek term haptesthai, which related to the sense of touch or to grasp. In the neuroscience and psychology prose, haptics is the study of human touch sensing [1]. More precisely human wisdom of touch can be categorised as two kind (i) kinesthetic receptors and (ii) cutaneous (tactile) receptors, which is associated with perception and manipulation. Kinesthetic includes location/configuration, motion, force, and compliance. Cutaneous receptors includes temperature, slip, texture, vibration and force [2]. It is well known that sight and touch are the two most treasured sense. Sight is centralized, broad, cognitive and passive but touch is distributed, narrow, physical and active moreover, touch is meaningful [3].The surge of curiosity in haptic technology was predominantly due to the development of virtual reality system. In the virtual reality and robotics fiction haptics is well-defined as genuine and virtual touch interaction between robots, humans, remote and real or simulated situations in several combinations.

Haptic is growing interdisciplinary space for research of human sensing and controlling objects in both real and simulated world [4]. Which characterized by a predilection for the sense of touch. A haptic interfaces are devices that enable manual interaction between real and virtual world device which subject physical interaction between the virtual model and user typically through an input output device like Phantom Omni [5], Falcon [6], sidewinder, haptic gripper, cyber glove, da Vinci surgical system and joystick wearable glove [1] that sense the body movement. Haptic technology heavily focused on theoretical foundation of manipulator design, sensing, actuation and control which is closely connected with robotics through various mechatronics devices. The haptic technology enables the user to interact and transform the virtual objects by providing tactile force feedback.

The principle behind all the haptic device is mapping or transferring the position and velocity of tool's tip to virtual object and supplying different number of DOF force feedback depending the mode of job handled by computer. For example functional haptic system and virtual reality technology can be used for maxillofacial surgical procedure training, which based on the tactile force feedback from the sensory module, senior doctors were capable to assess the proficiency levels of trainees [7]. The tele-manipulator system into the cardiac surgical procedure where the realistic force feedback aids to supervising the serious role in the endoscopic procedures [8]. The cardiovascular operation can be done based haptic imitation and interactive picturing of the beating heart [9]. In accessory due to the capability of force generation, haptic device can be utilized rehabilitation treatment and depend on the observation and state of recovery, specialists can suggest appropriate exercise to the patients [10, 11].This kind of simulation developed on the different framework are used in different application like automotive, tele-robotics, self-governing exploration of harmful working environment, entertainment, medical training, cleaning robot, medical surgery [12, 13] and molecular modelling[14]. In present scenario the most effective impact of haptic device is on the medical field like cardio vascular surgery, eye surgery, exoskeleton, brain tumor detection, medical training etc. Hence, the haptic integrated simulations are imminent to conventional method used in training and education medical field.

In the area of medical training [15] haptics has enormously changed the way trainees and house surgeons are trained. To train a surgeon, the traditional method have been used in medical field is first see, then do, and then teach. However the usage of simulation-based system which is incorporated with haptic technology, has become more extensive in medical field. Tactile force feedback and sensory feedback are two important terminology in all haptic device, and it has major role in medical surgery. In all kind of surgery the surgeon performing operation based on tactile force feedback getting from the patient. The surgery simulation has provided various information and features which cannot gained in current conventional training techniques. Virtual reality has major role in the haptic technology as the creation of virtual environment provide a better reality, performance, demonstration modelling, and cost effectiveness [14].

II. HAPTIC DEVICE

A haptic module is a feedback expedient that creates sensation to the skin or muscles or, as well as the sense of realistic touch, rigidity or weight. The feedback may be force, torque, audio and video or visual information. In human computer interaction haptic feedback implies both force and tactile information. Tactile or touch feedback implies the sensation felt by skin and tactile feedback allow user to feel temperature, compliance, configuration, texture variation, pressure, and vibration [2]. Force feedback fetches directional forces from different object and boundaries, weight of the grasping or gripping object, mechanical compliance and inertia of an object [16].

Haptic device permit users to feel, touch, and control 3D virtual object in the virtual environment which differ from input device like keyboard, mouse, joystick and output device like monitor and speaker as which allow data flow only in one direction [16]. While haptic devices are two way devices that follow user physical manipulation that is input and provide genuine touch sensation with onscreen event that is eventual output. Haptic devices may include various sensor like tactile, encoder, pressure, temperature and special motors like Johnson motor [2] piezo motor, vibration motor, Maxon motor[17], precision motor and DC brushless motor.

Ground based haptic devices and body based haptic devices are the major classification of general purpose commercial haptic device, which are used in most of the medical and research industry. Ground orient device includes force reflecting joystick and linkage based devices and body based devices includes gloves, exoskeletal, suits etc. The most prevalent commercial device used in medical and scientific research is linkage based system, which attached a stylus[16] at the tip. The arm tracks the positon and orientation of the stylus tip and it is efficient for exerting force on the sensitive tip of the pen. Haptic interface required highly sophisticated hardware and software to meet the required demand of haptics, it evaluate joint position angle and torque required to apply at the tip of the pen to feel the sense of touch. The great challenge in haptic device is inertial force, which introduce by mass of robotic arm and it is very hard to control because of updated demand and technology.

The haptic device “Phantom Omni” is used in most of the medical application which is a 3-DOF force feedback device and cost is around $10,000 to $10, 0000. As because high cost of commercial haptic device the main objective of our work is to design and implement a low cost 2-DOF haptic device shown in Fig. 1 for different medical procedure.

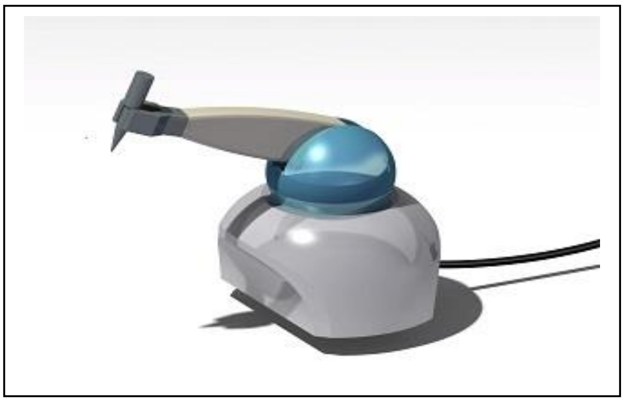

Fig 1. 2-DOF Haptic Device

III. DEVICE HARDWARE

In consideration of to interact with 2 DOF haptic device, users hold a stylus tip which is attached to the last joint. The intersection point of last two joint is treated as the Haptic Interaction Point (HIP) [5], where 2 DOF forces are experienced to the user. This 2 DOF device is configure for kinesthetic lively force feedback on the x axis and y axis from the measurement of instant position and orientation by use of joint sensor optical encoder [18]. This device includes two Maxon motor[17] with inbuilt encoder. The IEEE-1394 Fire Wire port is used as a communication interface [18] and this device confess real-time programming through Open Haptic Tool kit [1] class Toolkit 3D Touch [19], Chai 3D [20] which work with visual C++. All the parts including base, links and other attachment was designed and fabricated through 3D printing technology.

IV. DEVICE KINEMATICS

In order to determine force and torque to the haptic device, the kinematics of the 2-DOF device have to be essentially considered. This segment enlighten the forward kinematics as well as inverse kinematics of position and velocity using the Denavit and Hartenberg [5] method. The Jacobian is evaluated and used to derive the force and reflected torque. Fig. 2, depicts the kinematics parameter and initial condition for joints of the 2-DOF haptic device. For mechanical trackers that use joint angle sensors, required a map between joint space and Cartesian space, say θ_1 and θ_2 are generalized joint variables x and y are the Cartesian coordinate system.

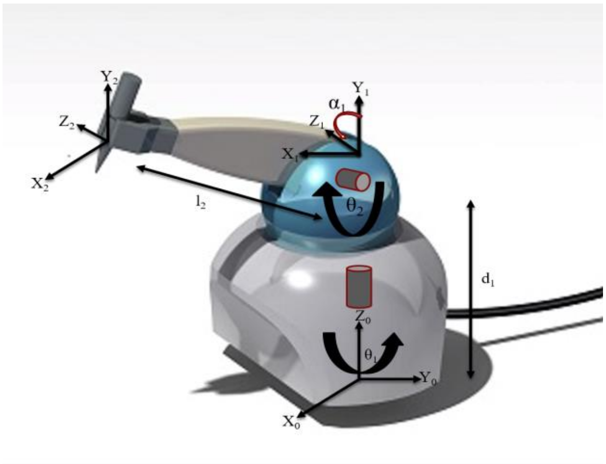

Fig 2. Initial Condition of 2-DOF Haptic Device

The forward kinematics model of the position establishing relationship between the operational coordinates and joint variables as shown in (1).

$$x= f(\theta) \tag{1}$$

Where $x \epsilon R^{3x1}$ denotes operational coordinate vector and $\theta \epsilon R^{3x1}$ joint coordinate. The axis of rotation θ_1 and θ_2 will be causes a coordinate transformation to translation from the initial position of pen tip point (0, 0, 0).

A. Forward kinematics

The graphical model has been generated using Direct Kinematics equations of the Robot arm. For the robot arm, the end effector orientation and position with the given joint angles and link lengths were calculated.The Fig.2 depicts the free body diagram of the 2 DOF Planar Robot used for the calculation of the Direct Kinematics equations.

From the Fig. 2, l_1 and l_2 are the length of the link, d_1 is the distance between X_n and X_{n+1} axis, θ_1 and θ_2 are the angle of rotation two revolute joint R1 and R2, α is the angle between X_{n+1} and Z_n axis. The Table I represent 2 DOF haptic device kinematic parameter.

TABLE I. Haptic Device Kinematic Parameter

LINK	θ	α	A	d
1	θ_1	90^0	0	d_1
2	θ_2	0^0	l_2	0

Substitute the above kinematics parameter in the Denavit and Hartenberg matrix will results

$$T={}^0A_1.{}^1A_2= \begin{bmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_2 & -s_2 & 0 & l_2c_2 \\ s_2 & c_2 & 0 & l_2s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Where c_1=cos θ_1, c_2=cos θ_2, s_1=sin θ_1, s_2= sin θ_2

From the above matrix

$$P_x= c_1c_2l_2 \tag{3}$$

$$p_y= s_1c_2l_2 \tag{4}$$

$$p_z= d_1+s_2l_2 \tag{5}$$

B. Inverse Kinematics

Inverse kinematics compute the joint angle as a function of Cartesian coordinates and it is characterized by (6)

$$\theta=f^{-1}(x) \tag{6}$$

For the robot arm, the end effector orientation and joint angle with the given position and link lengths were calculated.

$$T={}^0A_1.{}^1A_2= \begin{bmatrix} c_1c_2 & -c_1s_2 & s_1 & c_1c_2l_2 \\ s_1c_2 & -s_1s_2 & -c_1 & s_1c_2l_2 \\ s_2 & c_2 & 0 & d_1+s_2l_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

The above matrix is in the form of

$$H= \begin{bmatrix} \mathbf{n}_x & \mathbf{o}_x & \mathbf{a}_x & P_x \\ \mathbf{n}_y & \mathbf{o}_y & \mathbf{a}_y & P_y \\ \mathbf{n}_z & \mathbf{o}_z & \mathbf{a}_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

From the above matrix $\frac{P_y}{P_x}$

$$\frac{Py}{Px} = \frac{l_2 sin(\theta_1) .cos\,(\theta_2)}{l_2 cos(\theta_1) .cos(\theta_2)} \tag{9}$$

$$\theta_1 = tan^{-1}\left(\frac{P_y}{P_x}\right) \tag{10}$$

Pre-multiply ${}^0A_1.{}^1A_2$ with $({}^0A_1)^{-1}$ then

$$\frac{Px.cos(\theta_1)+Py.si\,n(\theta_1)}{Pz-d1} = \frac{l_2.cos\,(\theta_2)}{l_2.sin(\theta_2)} \tag{11}$$

$$\theta_2 = \tan^{-1}\left(\frac{(P_z-d_1)}{Px.cos(\theta_1)+Py.si\,n(\theta_1)}\right) \tag{12}$$

C. Forward Kinematics of Velocity

Where $\dot{x} \epsilon\ R^{3x1}$ denote the operational velocity vector, $J \epsilon R^{3x3}$ are represent Jacobian matrix of the haptic device and $\dot{\theta} \epsilon R^{3x1}$ denote joint velocity vector. Forward kinematics of velocity[3] compute the co-ordinate velocity as a function of joint angle velocity and it is defined by (13).

$$\dot{x}=J\dot{\theta} \tag{13}$$

Deriving Jacobian matrix from the equation (3), (4), (5).

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} . \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \tag{14}$$

Where,

$$J_{11}= -l_2 * cos\theta_2 * sin\theta_1 \tag{15}$$

$$J_{12}= l_2 * cos\theta_1 * sin\theta_2 \tag{16}$$

$$J_{13}=0 \tag{17}$$

$$J_{21}= l_2 * cos\theta_2 * cos\theta_1 \tag{18}$$

$$J_{22}= -l_2 * sin\theta_1 * sin\theta_2 \tag{19}$$

$$J_{23}=0 \tag{20}$$

$$J_{31}= 0 \tag{21}$$

$$J_{32}= l_2 * cos\theta_2 \tag{22}$$

$$J_{33}=0 \tag{23}$$

Jacobian matrix is used to determine the guided track and motion planning[21] during haptic directed task and also used for mapping actual reflected force on virtual engine to a torque vector essentially be applied by the actuator joints of the haptic device.

D. *Inverse Knematics of velocity*

Inverse kinematics of velocity[3] is defined by (24)

$$\dot{\theta} = J^{-1}\dot{x} \tag{24}$$

Where $J^{-1}\ \epsilon\ R^{3x3}$ relates to the inverse of the Jacobian matrix is given below.

$$J^{-1} = \frac{adj(J)}{det(J)} \tag{25}$$

Where *adj (J)* $\epsilon\ R^{3x3}$ define the Jacobian matrix ad joint and *det (J)* denotes its determinant.

$$det\ (J) = 0, \tag{26}$$

Many device will have configuration at which the Jacobian matrix is singular. Which implicate that the device has lost one or more DOF at its Cartesian space. This method can be used to determine values of θ at which device cause singularities.

V. 2-DOF HAPTICDEVICE INTERFACE

Haptic system includes three parts namely user interface, computer interface and mechatronics system called haptic device. Haptic interface establish a link between user and computer. The Human operator is simulated by tactile, visual, kinesthetic data. The initial state of the visual and tactile, the user to adapt the virtual environment with force signal response and the deviations are displayed the display unit[19], thereby updating new dynamic environment of interactions. The position data can obtained from the user by computing the position and orientation of stylus tip attached to the link. The encoder attached to Maxon motor will calculate the position orientation hence the velocity from the forward kinematics of haptic device. Using this information the controller is capable of calculating equivalent force/torque by generating corresponding pulse width modulation signal to respective motors. To compute the force feedback that generate the user kinesthetic is used to map the force to torque in respective joints[18].

A. *Kinesthetic force feedback*

For mechanical trackers that use joint angle sensors, required transformation between joint space and Cartesian space, say θ_1, θ_2 are generalized joint variables x, y are the Cartesian coordinate system. Forward kinematics results end position of device from the joint angles. To compute stylus tip velocity from joint velocity we use Jacobian matrix.

$$\dot{x} = J\dot{\theta} \tag{27}$$

To calculate essential joint torques from the reflecting force, Jacobian matrix is used again. To relate joint torques to end effector force the following equation (28) can be used.

$$\tau = J^T f \tag{28}$$

This is the fundamental equation used in multi degree of freedom haptic devices. This equation is procure from the principle of virtual work, which define that shifting the coordinate frame does not alter the whole work of the system. Where $\tau\ \epsilon R^{3x1}$ describes the torques vector, J^T is the transpose of Jacobian matrix and $f\ \epsilon R^{3x1}$ is the force vector defined by the interaction in the virtual environment. The force vector at the contact point is defined as $\overrightarrow{F} = (Fx_i + Fy_i + Fz_i)N$ then $\tau_1 = (J_{11}F_x + J_{21}F_y + J_{31}F_z)Nm$, $\tau_2 = (J_{12}F_x + J_{22}F_y + +J_{32}F_z)Nm$ $\tau_3 = (J_{13}F_x + J_{23}F_y + J_{33}F_z)Nm$ and define the torque in each joint. To determine the force that is generated on actuator to sense of presence of a virtual skin to this end different algorithm such as constrained Lagrangian [22], Hooke low [22], etc. can be used.

B. *Characteristics of The 2-DOF Haptic Device*

Minimum necessity to use this device compulsory a PC Pentium 4 processor with 1GHz and 1GB of RAM, two Intel processors and a GForce3 video card under windows XP environment. Programming language required is visual C++ and data analysis, Graphic test required Matlab 7.0. To program virtual skin model, Open GL is also can be used instead of C++. Chai 3D [20],Class 3D Touch [19] and Open haptic Toolkit [1] is used for haptic rendering.

VI. KINEMATICS ANALYSIS OF 2-DOF HAPTIC DEVICE

The validation of kinematics of 2-DOF haptic device corresponds to the kinematic chain [18] depict in the Fig. 3. First step is to read operational coordinates x_{hh} and $\dot{x}_{hh}$ through Class 3D Touch which defined keenly by human operator. In second step this result is used in the inverse kinematics of position and inverse kinematics of velocity for to define θ and $\dot{\theta}$. Subsequently in third step this vector are evaluated at forward kinematics of position and forward kinematic of velocity x_m and $\dot{x}_m$, and compared with those value obtained in first step which have been in Δ=0.005mm and $\dot{\Delta}$=0.005mm/seg with graphical display purposes.

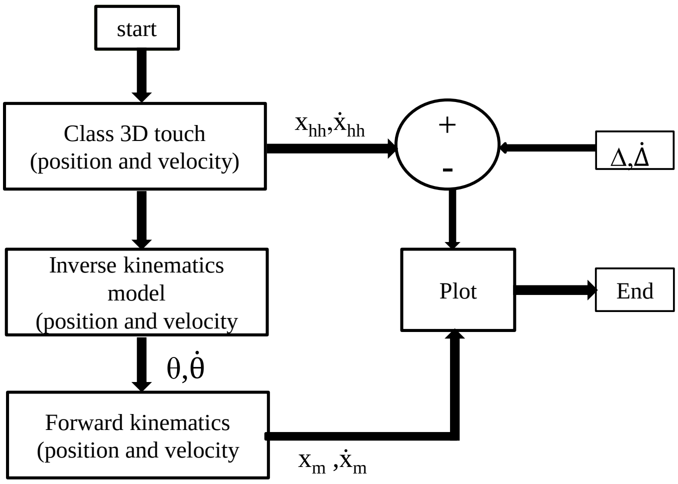

Fig 3. Kinematic Chain of Haptic Device

VII. 2-DOF HAPTIC DEVICE WORKSPACE

The main contemplation in decisive a haptic device's applicability for the potential applications are its workspace restrictions. The inertia of haptic device increases when the mass of the links increases, which diminishes the dynamic range. To estimate the workspace the maximum and minimum angle of each joints should be known. Since the 2-DOF device upholds the pen tip interaction of the Phantom Omni[19], it is sensible to deliberate the Omni's positional workspace to define applicability of the 2-DOF Haptic device. The joint limitation for the active joints steering the Phantom Omni's spherical wrist [17] prominent to the positional workspace are.

$$-56^o < \theta_1 < 56^o, \quad (29)$$
$$-103^o < \theta_2 < 0^o,$$

Based on this workspace limitations Fig. 4 depicts the positional workspace for the 2-DOF haptic device as a 2D XY plot.

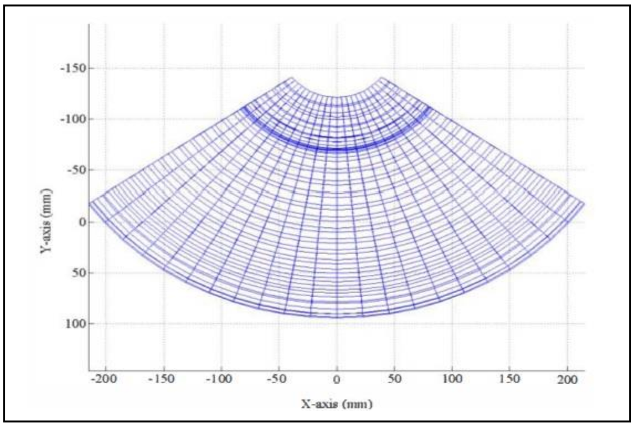

Fig 4. 2-DOF Haptic Device Positional Workspace Plot

VIII. CONCLUSIONS AND FUTURE WORK

The final consequences that we signify in this paper permit to evaluate 2-DOF haptic device in medical training as a haptic device to human –machine interactions with virtual environment or mechatronic device with the haptic guidance purpose in different medical applications. Analysis of the 2-DOF haptic device's kinematics and workspace was conducted and the forward and inverse kinematics for the 2-DOF device formulated. This paper authenticate complete kinematics analysis of 2-DOF haptic device and confirm the mathematic model.

Future work comprises performance measure of haptic device, modelling of tooth model, various skin surfaces with different skin parameter, interfacing haptic device with virtual model of skin and tooth model via haptic communication link and performance analysis of the system.

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