Synthesis and Design of a 2-DOF Haptic Device for Simulating Epidural Injection

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Abstract—This work demonstrates the synthesis and design of a 2-DOF (Degrees Of Freedom) parallel haptic device intended for use in virtual simulation of medical procedures, e.g., epidural injection. The process involved choosing a right kinematic architecture of the mechanism, calculation of the end-effector forces, CAD modeling, stress analysis and a rapid prototyping of the device. We chose a pantograph mechanism with congruent joints i.e., effective base link length equal to zero. Maximum forces that can be exerted at the end-effector over the usable workspace were calculated from the stall torque of the actuators. The enhancement in the actuator torque was achieved by employing a capstan torque-amplifying transmission mechanism.

Keywords: CAD modeling, haptics, parallel manipulators, rapid prototyping

I Introduction

Haptics is an emerging interdisciplinary field of study of human sensing and manipulating objects in both real and virtual world with both teleoperated and proximal environments. Haptic interfaces are devices that enable manual interactions with virtual environments or teleoperated remote systems [1]. A spectrum of haptics applications have emerged recently in the area of medicine, rehabilitation, education, entertainment, product design, navigation and others.

The haptic interface provides force feedback and complex haptic feelings such as texture, compliance, temperature and others. Usually the haptic interfaces are special robotic devices with a control system updating at 1-kHz. A variety of such haptic devices have been developed both at the commercial scale and in the research arena. A comprehensive list of key application areas and devices has been reported [2].

In the area of medical training [3], [4], haptics has immensely changed the way trainees and medical residents are trained. One such application in medical science is epidural injection.

Epidural injection is a form of regional anesthesia involving injection of drugs through a catheter placed into the epidural space [5]. Injecting medication into the epidural space is primarily performed for analgesia (pain relief). Epidural anesthesia requires a high level of technical proficiency to avoid serious complications, and is always performed by a trained anesthetist. It has caused several deaths by cardiac arrest when epidural anesthetic has been accidentally inserted into vein instead of epidural space in the spine. Currently, residents in post graduate medical training and other trainees learn to administer epidural injection by performing supervised procedures on real patients or less frequently on cadaver specimens [6]. The technique involves inserting the needle into a specific region (epidural space) of lower lumbar region (L4, L5). Figure 1 depicts the various regions of tissues (of varying stiffness) through which the needle has to pass during the injection.

Fig. 1. Various layers encountered in epidural injection process ©

Haptics based injection simulation replaces the requirement of cadavers or animals for these trainings. A virtual environment of lumbar vertebra and the tissues is simulated using computer graphics, containing the properties (geometry and stiffness of tissues and bones).
The end-effector of the haptic interface device acts as a syringe and is reflected as a virtual needle on the screen. The movement of the virtual needle is completely dependent on the movement of the end-effector of the haptic interface device. The resident trainee keeps his eyes on the virtual lumbar vertebra displayed on the screen of a computer and manipulates the end-effector. As the virtual needle interacts with the lumbar vertebra, forces similar to the forces felt in real injection process are generated at the end-effector (syringe). This leads to a complete immersion into the injection process.

We here focus on synthesis, design and the rapid prototyping of one such haptic interface device that can be used for epidural injection simulation.

II. Mechanism Synthesis

Haptic devices essentially being a human-machine interface must have general features of an ergonomic design. In particular, it should be compact and the operating workspace should be large in relation to the size of the device itself [7]. We selected a 5-bar closed-loop mechanism (Fig. 2) to generate haptic feedback in 2-degrees-of-freedom (DOF) environment. Parallel mechanisms overweight their serial counterparts in many ways. As pointed by Merlet [8], parallel mechanisms are interesting for the reason that when the actuators are locked, the manipulator remains in its position; which is an important safety aspect for certain applications, such as medical robotics. Also because of their quality for precise positioning and increased structural stiffness, they are preferred over their serial counterparts, which is favorable for haptics application [9].

Note that inserting a needle into a body is a one-direction motion requiring only one-DOF device. However, to provide some degree of flexibility to a trainer along X and Y directions, a 2-DOF system is proposed, as shown in Fig. 2.

Some 1-DOF and 2-DOF haptic devices have already been reported in the literature with and without torque enhancers and with a non-zero base length [10], [11]. Although the use of non-zero base length simplifies the robot design, it reduces the mechanism workspace (Fig. 3a). By placing the active (base) joints congruently, the reducing material usage while still maintaining the same utility as other 2-DOF closed loop manipulators.

III. Kinematics

The kinematic diagram is illustrated in Fig. 2. This device simulates forces within a planar rectangular workspace. The link lengths have been chosen of uniform dimension of 100 mm each with the length of ground link equal to zero. The choice for the link lengths has been through intuition to achieve a reasonable workspace for our application. Thus, the usable workspace (singularity free) dimensions are 170 mm wide and 70 mm long. The choice for workspace was restricted due to the fact that parallel manipulators have singularity within the workspace in addition to the boundary singularities.

Length-wise the workspace spans a distance 100 mm to 170 mm from the motor. Width-wise the motor is located at the workspace’s midpoint (Fig. 3b) such that it is 85 mm from the joint at one end and another 85 mm from it at the other end. This workspace provides ample length for an injector to simulate traveling from the back to the epidural space in question, while also providing the workspace with a large width for a multitude of other planar virtual environments and other possible uses.

Beyond just deciding upon a 2-DOF pantograph, a more specific pantograph with uniform link lengths and
torque enhancers was selected. The area of usable workspace is shown as a rectangle in Fig. 3b, which was obtained using the following kinematic constraints [12]:

\[(x - a, \cos \theta_j)^2 + (y - a, \sin \theta_j)^2 = a_i^2 \]  \hspace{1cm} (1)

\[(x - a, \cos \theta_j)^2 + (y - a, \sin \theta_j)^2 = a_i^2 \]  \hspace{1cm} (2)

where, \(x, y\) are the end-effector coordinates and \(a_i\), for \(i = 1, \ldots, 4\), is the link length, as shown in Fig. 2.

### IV. Static Analysis

Static analysis is of practical importance for determining the quality of moment and force transmission through the various joints of the mechanism. It serves as a basis for sizing the links and bearings of the mechanism and for selecting appropriate actuators [13].

The device was analyzed for the forces at the end-effector due to the stall torques of both the motors enhanced by a factor of 10. We chose actuators from maxon motors [14] (Stall Torque: 131 mNm each). This was done as the device was intended to be used in multitude of applications. Stall torque being the maximum torque a motor can exert at zero angular velocity. A Matlab code was written to plot the force distribution over the usable workspace (Fig. 4). Forces at the end-effector were calculated on the basis of stall torques of the two motors. Four typical cases of torque direction were taken (cw-cw, cw-ccw, ccw-cw, ccw-ccw) to find the maximum forces at the end-effector in both \(x\) and \(y\) directions. Force distribution along \(y\) (axial direction) and \(x\) axis (radial direction) for the case when torque 1 is clockwise (cw) and torque 2 is moved counter-clockwise (ccw). The results are shown in Fig. 4 and Figs. 4 and 5, respectively.

For a parallel mechanism, the joint-rates are related to the end-effector twist by:

\[ J_x \ddot{x} = J_\theta \dot{\theta} \]  \hspace{1cm} (3)

where, \( \dot{x} \equiv [\dot{x}, \dot{y}]^T \) is the end-effector twist and \( \dot{\theta} \equiv [\dot{\theta}_1, \dot{\theta}_3]^T \) is the joint-rates, whereas \( J_x \) and \( J_\theta \) are known as the forward and inverse Jacobians. Here, \( J_x \) and \( J_\theta \) matrices for the system are obtained by differentiating eq. (1) and (2) as

\[ J_x = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \quad \text{and} \quad J_\theta = \begin{bmatrix} \beta_1 & 0 \\ 0 & \beta_2 \end{bmatrix} \]  \hspace{1cm} (4)

in which \( \alpha_{11} = x - a, \cos \theta_j; \quad \alpha_{12} = y - a, \sin \theta_j; \quad \alpha_{21} = x - a, \cos \theta_j; \quad \alpha_{22} = y - a, \sin \theta_j; \quad \beta_1 = a, (y \cos \theta_j - x \sin \theta_j) \) and \( \beta_2 = a, (y \cos \theta_j + x \sin \theta_j) \). The overall Jacobian for the mechanism is given by:

\[ J = J_x J_\theta \]  \hspace{1cm} (5)

which relates the joint-rates with the end-effector twist or velocities as

\[ \dot{\theta} = J \dot{x}. \]  \hspace{1cm} (6)

In eq. (6), the 2x2 matrix, \( J \), is as follows:

\[ J = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \beta_1 & \beta_2 \end{bmatrix} \]  \hspace{1cm} (8)

The end-effector force vector is then obtained as:

\[ F = J^T \tau. \]  \hspace{1cm} (9)

where \( F \equiv [f_x, f_y]^T \) and \( \tau \equiv [\tau_1, \tau_3]^T \) - \( \tau_1 \), \( \tau_3 \) being the torques at the enhanced devices due to the two motors located at joint 1 and 3, respectively. We found that the maximum force at the end-effector along \( x \) and \( y \) direction for all possible combinations of motor torques was 15 N and 40 N respectively.
V. Design Issues

Once the forces on the end-effector had been determined, the process of designing the pantograph could begin. The task was open-ended as there were no specific parameters, but there were three general modeling concerns to deal with: 1) could the design actually allow the end-effector to freely move about the pantograph’s workspace without mechanical interference? 2) how heavy would the links be? and 3) how would they handle the stresses resulting from the forces on the end-effector?

(a) Links one over the other

(b) Architecture with hinges at the ends

(c) Joint structure of ‘b’ architecture.

Fig. 6. Design iterations for the pantograph

In order for the pantograph to function properly, its links had to be designed to fit around each other such that they would not come into contact no matter where the end-effector was located within the workspace. There were two general pantograph designs for dealing with this problem: one was to offset the links such that two of the links would be on top of the other two as shown in Fig. 6(a), therefore allowing all links with full range of motion.

(a) Hollow cross-sectional links with hinges at the ends

(b) Joint structure of ‘a’ architecture

(c) Hollow cross-sectional links with trapezoidal front links

(d) Joint structure of ‘c’ architecture

Fig. 7. Other possible configurations for the pantograph

The other design was to put all of the links in plane, but to design hinges on the ends of the links that would interlock with adjacent links as shown in Figs. 6(b) and c. Both methods came with their own set of flaws. The first method often led to the links displacing greatly due to the forces on the end-effector, while the second resulted in stress concentrations at the locations of the joints. The range of motion of the first design spanned the area of the workspace independent of the link design.
iterations, it was discovered that the flexibility of the second method was mostly dependant on the hinges at the end-effector and motor positions. Eventually the first design method was selected for its simple link architecture and joint design.

The weight of the links was also a major concern. Haptic devices are only beneficial to the extent that they can accurately simulate an environment and fully immerse the user in a virtual realism. The heavier the link, the more inertia it has. Ideally, the inertia of the device should be much less than the inertia of the finger tissue displaced by the device in order to establish a robust casual relationship between an input force signal and perceived motions. This requirement is, however, the most difficult to achieve [7]. Reducing the weight of the pantograph meant reducing its volume and / or using a less dense material. If the workspace dimensions were taken as fixed then that meant the volume of the link could not be reduced by changing the link’s length. Thus, the possible ways to change the links volume would be to use thinner segments, shorter segments, and or hollow segments. However, these methods often result in reduced support for links increasing the stresses on them. Even if these increased stresses do not result in yielding the parts, they would often result in displacement of the end-effector, which damages the immersive feel of the haptic device. As in the case of changing the volume, using less dense materials often results in the link’s deformation and yielding more easily, as less dense materials often have lower yield strength and smaller Young’s Modulus.

VI. Stress Analysis

The primary concern for every model was in the stress analysis phase of its design. First the CAD model of the device was developed using Autodesk Inventor 2010 [15]. Using the stress analysis module in Autodesk Inventor 2010, various models of the device (Figs. 6, 7) were tested by evaluating the stresses and strains they underwent as the end-effector encountered different forces throughout the workspace. The testing amounted to moving the end-effector to a position in the workspace, usually to a point in a corner or along an edge, fixing the motor joint so that the pantograph became static, and then applying the forces to the end effector that correspond to the location from the force analysis.

In order to account for some factor of safety, higher values of forces were considered in addition to the maximum value of forces from statics. Autodesk uses von Mises yield criterion for stress analysis. In general the higher stresses were along the links concentrated at the joints of the pantograph, specifically the motor joint (max 6.985 MPa).

These stress concentrations at joints would be greatly amplified if the links were hinged. The two links that connected to form the end-effector underwent far less stress than the two links that connected to form the motor joint (around 3.7 MPa). Stresses also concentrated along edges, such as the edges of a square cross section link. Comparatively, the links underwent much smaller stresses except for the area near joints. It was determined that, as long as the links were supported at certain high stress sections along their lengths, they could be manufactured with lightweight materials and with hollowed sections of the links. Doing so resulted in an overall reduction in the system’s inertia, a value that all haptic designs look to minimize [16]. Figures 8 and 9 depict the stress analyses for the final design selected for the pantograph. In Figs. 8 and 9, the extreme and nearest corners of the workspace are with respect to the base joint of the device. Although stress analysis was carried
out at various points in the usable workspace, the above figures depict the maximum stresses encountered during the whole analysis.

VII. Rapid Prototyping

For the model produced at Rapid Prototyping facility of IIT Delhi [17], Polyamide PA 2200 with yield strength and Young’s Modulus of 45 MPa and 1700 MPa respectively, was used. The features of the components for rapid prototyping are explained below:

A. Links:

As shown in Fig. 10, the motor (rear) links were designed with built-in torque enhancers and are trapezoidal in shape, with the area of cross-section decreasing towards the front. This trapezoidal design allowed the links to easily handle the higher stresses near base-end as discussed previously without adding unnecessary mass.

B. Joints:

The links were offset to make hinge construction easier. Furthermore, the links were designed with large cylindrical hinges to handle joint stresses.

C. Torque enhancers:

The torque enhancers were built onto the motor links offset above and below them. Their locations are asymmetric (Fig. 10), but this design was necessary in order to have enough room for them. The torque enhancers were designed to provide 10 times torque amplification to a motor shaft of 9 mm.

D. Housing:

Designing a housing for this particular pantograph was a little difficult, as there were many moving components that had to be fit together without interfering with one another. Although somewhat bulky, the finalized housing model provided support for the pantograph and its motors without limiting the pantograph’s motion. Figure 12 shows the Rapid Prototype (RP) of the pantograph with housing.

The device was assembled carefully to ensure that there was no play and interference at the joints. High quality stainless steel journal bearings were used in the joints to ensure no play.

VIII. Summary

As shown in the final RP model (Fig. 12), the pantograph based system is an affordable device capable of simulating a 2D haptic environment. The system was synthesized and designed from the kinematic movement and mechanical strength point of view. In the next phase, it will be tested under a set of control laws for evaluating its performance as a haptic device. The device is intended to be put inside a human lower-back mannequin.

The contribution of this work lies in its systematic approach in synthesizing and analyzing a novel design for the 2-DOF haptic device meant for the epidural
injection. The novelty is in the design of torque enhancers and the link shapes along with their internal structures based on stress analysis.

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