A Compact 3-DOF compliant Serial Mechanism for Trajectory Tracking with Flexures Made by Rapid Prototyping

Su Zhao, Yan Naing Aye, Cheng Yap Shee, I-Ming Chen and Wei Tech Ang

Abstract—To fulfill the needs for accurate trajectory tracking with large displacement in a handheld instrument, a 3-DOF serial compliant mechanism is developed. The mechanism is compact with a total length less than 150 mm and a maximum diameter of 22 mm. Two flexures are developed using different rapid prototyping techniques: one 3-DOF flexural lever made of Vero-Gray by Polyjet and a 1-DOF translational flexure made of stainless steel by Direct Metal Laser Sintering (DMLS). Analytical and Finite Element (FE) models are developed for the proposed flexural mechanisms. Experiments are conducted on a prototype. To improve the tracking accuracy, the hysteretic nonlinearities of the system are modeled using Prandtl-Ishlinskii model. Inverse feedforward controller is implemented to linearize the relationship between input and output. The tracking performances of the system. The total tracking errors are identified individually for each axis and then compensated. Tracking performances of the tool tip are evaluated experimentally with different inputs. The inverse kinematics is solved and hysteresis compensation can be done on a system level, the hysteresis compensation is higher than 4\(^\mu\)m for the same application as the previous parallel mechanisms, but are not practical for production of small quantities, such as for research purpose, due to high cost. However, while the compactness and complexity of the flexure design further increase, at one point, it will become either impossible or extremely expensive to manufacture such flexures using conventional machining, EDM or casting and moulding.

For more complicated structures like flexure hinges, special machining methods such as Electric discharge machining (EDM) have to be used. Casting or inject moulding allow more complicated designs, but are not practical for production of small quantities, such as for research purpose, due to high cost. However, while the compactness and complexity of the flexure design further increase, at one point, it will become either impossible or extremely expensive to manufacture such flexures using conventional machining, EDM or casting and moulding.

In this paper, a flexure based serial mechanism, aiming for the same application as the previous parallel mechanisms, will be presented. Being serial with no rotational movements, the kinematics is straightforward. Each axis can be driven individually by actuating the corresponding actuator. Therefore, hysteresis compensation can be done on a system level, between the input to the actuator and the output at the end effector. Improved tracking accuracy is expected from the proposed serial mechanism to better fulfill the requirement of the handheld application.
II. DESIGN OF THE COMPLIANT SERIAL MECHANISM

A. Design Description

The proposed serial mechanism (see Fig. 1(a) and 1(b)) consists of two shearing, two longitudinal piezoelectric actuators, one flexural lever, one translational flexure and a housing. It can produce three dimensional translational motions. The two shearing actuators (P152.10 from Physik Instrumente) are stacked together to generate translational motions in X and Y axes. The travel range of the shearing actuators is normally small; therefore, the flexural lever is connected on top of the shearing actuators to mechanically magnify the displacement, with its center column connected to the actuator and its edge to the housing. When the shearing actuator deforms in X or Y direction, a magnified displacement in -X or -Y direction will occur at the free end of the lever. The actual magnification factor is subjected to the length of the tool mounted on the flexural lever. The two longitudinal actuators (P885.90 and P885.50 from Physik Instrumente) are stacked together to increase the travel range. They are placed behind the shearing actuators through the translational flexure. One end of longitudinal actuators is connected to the fixed housing, while the other end pushing the translational flexure and moving the shearing actuators in Z (axial) direction. The translation flexure made of stainless steel provides sufficient stiffness for pre-loading the longitudinal actuators.

B. Design Requirement

The application of the proposed flexural mechanism is a hand-held surgical instrument [6], [7]. The instrument senses the tremor motion of human hand and compensates it actively by controlling the mechanism. In order to be held by hand, the instrument has to be compact and light. The external load on the flexure in this application is in mN range; therefore, the flexural lever needs not to be very stiff. However, the translational flexure should be stiff enough to provide sufficient (up to 50 N) pre-loading forces to the piezoelectric actuators while allowing a travel of 50 µm, which is the maximum amplitude of hand tremor. The mechanism should be able to operate at frequencies up to 12 Hz, which is the maximum frequency of human hand tremor [8]. Higher stiffness will lead to higher first resonant frequency, but it will also reduce the maximum travel of the actuator. So, the stiffness \( k_z \) in Z axis of the mechanism (combined stiffness of the translational flexure and the flexural lever) must be designed carefully to reach a balance between loss of travel range and sufficient stiffness. Given the desired travel range, \( k_z \) can be calculated using the following equation [9], [10]:

\[
\Delta L = \frac{k_{\text{piezo}}}{k_z + k_{\text{piezo}}} \Delta L_0
\]

In which \( \Delta L_0 \) is the maximum unloaded nominal travel range of the piezoelectric actuator, \( \Delta L \) the realized travel range under load. In this study, the stiffness of the stacked longitudinal piezoelectric actuators \( (k_{\text{piezo}}) \) is around 20 N/µm and the maximum unloaded travel is 47 µm. To reach 40 µm travel under load, the maximum stiffness \( k_z \) is calculated as 3.5 N/µm.

C. Design of the Flexures

The flexural lever shown in Fig. 2(a) consists of a central column linked to a rigid outer ring by four leaf type springs. One end of the central column is linked to a connector (a short cylinder to connect to the shearing actuator) by a flexural ball joint. It has three degree of freedom, which are translation in Z axis and rotation along X and Y axes. The translational flexure (see Fig. 2(b)) consists of three sets of four limb leaf type springs similar to the upper part of the flexural lever. By stacking the three sets, rotation of the central column along X and Y axes is constrained, remaining just one degree of freedom which is the translation in Z axis.

Because the displacement being analyzed here is small, the stiffness \( (k_y) \) of a single leaf type spring can be calculated analytically using linear beam theory as [11]

\[
k_y = \frac{Ewt^3}{L^3}
\]
In which $E$ represents Young’s modulus of the material, $w$ the out of plane width of the beam, $t$ the thickness of the leaf and $L$ length of the leaf.

With the assumption of small displacement, the axial translation requires only simple beam bending. The range of motion is limited only by the yield stress $\sigma_{yield}$ of the material. Due to the parallel structure, the range of motion of the flexure is equal to that of a single beam. From linear beam theory, the maximum deflection $\delta_{y\max}$ is,

$$\delta_{y\max} = \frac{L^2\sigma_{yield}}{3Et}$$

(3)

The initial dimensions of the flexures are determined using the above equations and considering the size and weight requirements of the application. Finite Element (FE) models are then developed based on the initial designs using software package ANSYS. The stiffness and compliant under loads are simulated by performing static structural analysis. The simulation results are shown in Fig. 3(a), 3(b), and Fig. 4. After conducting a number of design iterations until the design criteria is achieved, the final dimension of the flexure are determined. For the translational flexure, $L = 9\text{mm}$, $t = 0.5\text{mm}$, $w = 3.5\text{mm}$. For the flexural lever, $L = 9\text{mm}$, $t = 0.8\text{mm}$, $w = 4\text{mm}$, $d = 0.7\text{mm}$, in which $d$ represents the minimum diameter of the flexure ball joint. The calculated stiffness in Z axis is 2.5 N/µm for the translational flexure and 0.1 N/µm for the flexural lever.

![Fig. 3. FE analysis of the flexural lever, (a) deformation in Z axis and (b) deformation in X axis](image)

The FEM model is then used to predict the resonant frequency in the working axis of the flexures. For flexural lever, constrains are given as following: outer ring is fixed; the cylinder connector has freedom only in X, Y and Z translation. This is to simulate the situation when the flexure is mounted on the housing with the connector fixed on the shearing actuators. The first resonant modes are found at 2393 Hz, which is the center column rotating along X and Y axes. The mode shapes are same as shown in Fig. 3(b). The first translational resonant mode along Z axis is found at 1666.9 Hz with mode shape same as shown in Fig. 3(a). For the translational flexure, with the supporting columns fixed, the first natural mode in Z axis is found at 2504 Hz. The mode shape is same as shown in Fig. 4. All the first natural frequencies are safely far away from the maximum operating frequency of 12 Hz. Therefore, there is no risk of exiting the natural mode of the structure during operation. Fig. 3(a), 3(b) and Fig. 4 show the deformation and Von Mises stress distribution on the structure when flexure is subjected to forces in their working directions.

D. Fabrication of the Flexures

In this application, RP process Polyjet is used to build the flexural lever which has an accuracy of 0.1mm. The material used is VeroGray with modulus elasticity of 3.0 GPa and yield stress of 60 MPa. More properties of VeroGray can be found in [12]. VeroGray is jetted onto the build tray in thin layers of 16 µm and the part is built layer by layer. Each layer is cured by UV light immediately after it is jetted onto the build tray and can be used immediately.

Direct Metal Laser Sintering (DMLS) is used to build the translational flexure. The material used in this process is stainless steel with modulus elasticity of 196 GPa and yield stress of 1.3 GPa. DLMS produces metal components that are 99.99 percent dense, directly from 3D CAD data. The parts produced are comparable to a good investment cast part and the mechanical properties are comparable to those of a cast or machined component.

III. EXPERIMENTAL INVESTIGATIONS

A. Experiment Setup

In order to examine the proposed flexural mechanism, an experiment setup is built as shown in Fig.5. The 3-D displacement of the tool tip is measured by three capacitive sensors placed in X, Y and Z axes (capaNCDT 6019 from MICRON-EPSILON with resolution 0.2 µm, bandwidth 500 Hz, measuring range 0.2 mm). For measurement purpose, a metal cylinder (length 30 mm, diameter 8 mm) is mounted on the end of the flexural lever, which forms a magnification ratio of 6. The position of the sensor can be adjusted using the XYZ linear stage. PZT driving signal generation, hysteresis control and data acquisition are done using real time operating system QNX Nertrino. (National Instrument). The output driving signal is transferred through amplifiers (E-413 and E503 from PI) and then to the shearing and longitudinal actuators.

The pre-stressing force applied to the piezoelectric actuators can be adjusted by turning the screw at the other
end of the housing. When a force is applied to the flexure through the piezoelectric actuators, an electrical charge will be generated at the actuator. The generated charge is precisely measured using a charge meter (Type 5015A from KISTLER). The applied force is then be calculated out using the piezoelectric constants and the capacitance of the actuator. In such a way, the piezoelectric actuator becomes a build-in force sensor. Detailed equation for calculating the force from charge can be found in reference [13], [14].

In this experiment, a 50 N pre-stressing force is applied to the longitudinal actuators. The shearing actuators work bidirectionally, therefore, don’t need pre-stressing in the working directions.

B. Hysteresis compensation

Although, closed-loop displacement feedback control is able to give excellent position control, its bandwidth is often lower than feedforward controller due to the time consumption of the feedback loop. Kuhnen [15] and Kuhnen and Janocha [16] demonstrated that the PI operator is suited for real-time applications. In this study, an open loop feed-forward controller [15], [7] is used to remove the hysteretic effect.

Being a serial mechanism the total tracking errors can be identified individually for each axis and then compensated on the system level, which is not possible if parallel mechanism is used. Hysteresis exists both in the piezoelectric actuators and the plastic flexure. For each axis, the total hysteretic effect between the input voltage and the output displacement at the tool tip is modeled using the Prandtl-Ishlinskii (PI) model. After identifying the parameters experimentally, the weights are found by least-square minimization of the error function. Inverse PI hysteresis model is then calculated and used as a feedforward controller to linearize the hysteresis response (Fig. 6). Detail about the controller design can be found in the previous publications of the authors [17], [7].

C. Experimental results

A number of experiments are conducted to demonstrate the performance of the manipulator. Since X and Y axes have the same configuration and similar performances. Only plots of X and Z axes are shown. The first experiment is to measure the hysteresis effect before and after applying the feedforward controller. The results are shown in Fig. 7(a) and 8(a). It is obvious that after applying the hysteresis compensation control, the output is linearized, which indicates that the controller is effective.

![Fig. 7. Hysteresis compensation in X axis on a 10 Hz sinusoidal wave](image)

The next test is to actuate the actuator in a periodic sinusoidal in each axis. The frequency of input signal is 10 Hz, and the peak-to-peak amplitude is about 58 $\mu$m in X and Y axes, and 38 $\mu$m in Z axis. Fig. 9(a) to 9(b) and Fig. 10(a) to 10(b) show the outcome and Table I summarize the results. The Root Mean Square Error (RMSE) in Z axis is already near the noise level of the capacitive sensor (0.2 $\mu$m). The RMSE in X and Y axes are 3 and 4 times higher than that of Z axis, because the flexure lever magnifies the error. The maximum error (MaxE) in all axes are lower than 3 $\mu$m.

![Fig. 8. Linearization of a hysteretic plant using the inverse feedforward controller](image)

Fig. 11(a) to 11(d) shows the measured trajectories when the end effector is driven to move in a couple of straight lines.
TABLE I

<table>
<thead>
<tr>
<th></th>
<th>RMSE (µm)</th>
<th>MaxE (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>0.608/5.713</td>
<td>1.750/10.220</td>
</tr>
<tr>
<td>Y</td>
<td>0.860/5.812</td>
<td>2.970/10.119</td>
</tr>
<tr>
<td>Z</td>
<td>0.212/2.200</td>
<td>0.620/3.369</td>
</tr>
</tbody>
</table>

at the full driving range of each axis, at a frequency of 10 Hz along X-axis, Y-axis, Z-axis and Y = X respectively.

IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

A 3-DOF serial compliant mechanism is proposed in this paper. Design procedure and FE analysis of the flexures are presented. The fabricated prototype mechanism is compact with a total length of 147 mm and a maximum diameter of 22 mm. It is suitable and comfortable for handheld purposes. Two difference flexures are manufactured using Polyjet and DMLS. Experiments are conducted on the prototype. In order to improve the tracking accuracy, the PI hysteresis model is used to implement a feed forward controller for hysteresis compensation. The hysteretic nonlinearities of the system are successfully compensated. The relationship between input and output are linearized. The tracking errors at 10 Hz are investigated with different input signal. The RMSE in all three axes are more than four times lower than the previous manipulator. RMSE in Z axis is only 0.212 µm, near the noise level of the position sensors.

B. Future Works

Frequency responses in all axes will be investigated experimentally by inputting sweep sinusoidal signals. The manipulator will be operated at higher frequencies up to several hundred Hz. Tracking performances at deferent frequencies will investigated. The current hysteresis model is rate independent, which limits the performance at different frequencies. Rate dependent hysteresis model will be implemented in the future. The tracking accuracy could be further improved. Possible other application of the proposed compliant mechanism include enhancement of performance in microsurgery and cell micromanipulation.

REFERENCES

Fig. 10. Tracking result in Z axis of a 10 Hz sinusoidal wave

(a) without compensation

(b) with compensation

Fig. 11. 2-D pots of the end effector when driven to move in, (a) X-axis, (b) Y-axis, (c) Z-axis, and (d) X=Y