Design and analysis of a novel large-range 3-DOF compliant parallel micromanipulator

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Abstract
Compared with the traditional rigid mechanism, the flexible mechanism has more advantages, which play an important role in critical situations such as microsurgery, IC (integrated circuit) fabrication/detection, and some precision operating environment. Especially, there is an increasing need for 3-DOF (degrees-of-freedom) compliant translational micro-platform (CTMP) providing good performance characteristics with large motion range, low cross coupling, and high spatial density. Decoupled topology design of the CTMP can easily realize these merits without increasing the difficulty of controlling. This paper proposes a new three DOF compliant hybrid micromanipulator which have large range of motion up to 100 μm × 100 μm × 100 μm in the direction in the dimension of 90 mm × 90 mm × 50 mm, smaller cross-axis coupling (the max coupling only 2.5%) than the initial XY compliant platform in XY axial.

Keywords
Micromanipulator, compliant, cross-axis coupling, large range, nonlinear control

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Introduction
The traditional rigid 3-DOF platform is usually assembled by a single-DOF platform with stepper motor driven, which composed of a fixed base and a motion stage translating along X-, Y-, and Z-axes in a plane. Compared with traditional rigid platform, compliant micro platform has become one of the main branches of the mechanisms and robotic systems due to their natural merits, such as reduced number of parts, no friction, and so on¹² which make a CTMP more precise to have a variety of needs: cell manipulation,³⁴ scanning probe nano-lithography,⁵⁶ atomic force microscopy,⁷ IC or targets fabrication,⁸⁹ and data storage.¹⁰ So a desired high precision CTMP should have the large motion range, minimal cross-axis coupling, without increasing the complexity of controlling.

Regarding a number of 3-DOF compliant micromanipulators, researchers pay a lot of efforts from theory to application. However, most of them based on the traditional rigid body model such as 3-RRR, 3-PRR, 3-PSS, or 3-PUU¹¹–¹⁴ (P: Prismatic pair; R: Revolute pair; S: spherical hinge; U: Hooke vice), and rarely involves three translational micromanipulations.¹⁵–¹⁸

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Xu and Li\textsuperscript{14} presents the stiffness modeling of a three prismatic-universal-universal (3-PUU) compliant parallel manipulator with orthogonally mounted actuators, that is designed to provide three spatial translational DOF for nano-scale manipulation. Jensen et al.\textsuperscript{19} introduces a three degree of freedom XYZ Micromanipulator, which components on a platform using three legs, each composed of a slider mechanism and a parallelogram mechanism. Pinskier et al.\textsuperscript{20} presented a modular flexure-based micro/nano manipulator, which has a measured range of translational motion of approximately 38.9 μm. Yangmin et al.\textsuperscript{13,21} proposed a novel 3-DOF compliant parallel mechanism for solving the conflict between large stroke and high precision of the mechanism of large stroke and high resolution of the mechanism without a need for amplifier mechanisms. However, these compliant micromanipulators still have some shortcomings, such as small motion range, large coupling, complex structure, and non-pure translational motion.  

In this paper, the main research contents include the design of the new XYZ CTMP, the analysis of the corresponding performance our and the physical control experiment based on the previous research. The remainder of this paper is organized as follows. Section 2 designs a new 3-DOF CTMP based on the 4-PP (prismatic joints) model. Section 3 shows the corresponding performance our of the 3-DOF CTMP by FEA. Section 4 shows the experimental results for verifying improved XYZ CTMP based on hysteresis compensation control strategy. The last part is the conclusion.
Where $E$ is the material elastic modulus; $w$ is the width of the flexible structure; $t$ is the thickness of the flexible structure; $R$ is the radius of the circular, $v$ is Poisson’s ratio, $G = E/(2(1 + v))$.

According to the transformation of force and displacement from the coordinate $Oi$ to the coordinate $Oj$, the compliance of the free-end $Oj$ with respect to the ground can be derived by:

$$C_{oj} = T_{oi}^{oj}C_{oi}(T_{oi}^{oj})^T$$

$T_{oi}^{oj}$ is the compliance transformation from $Oi$ to $Oj$, which takes on the following form:

$$T_{oi}^{oj} = \begin{bmatrix} R_{oi}^{oj} & 0 \\ 0 & R_{oj}^{oi} \end{bmatrix} \begin{bmatrix} I \\ (p_{oi}^{oj})^T \end{bmatrix}$$

In this paper, we only need to study hinge force and movement of three directions: $X$, $Y$ axis force and linear displacement, around the $Z$ axis of couple and angular displacement. For the transform matrix:

$$T_{oi}^{oj} = \begin{bmatrix} r_{11} & r_{12} & 0 \\ r_{21} & r_{22} & 0 \\ 0 & 0 & r_{33} \end{bmatrix} \begin{bmatrix} 1 & 0 & p_y \\ 0 & 1 & -p_x \\ 0 & 0 & 1 \end{bmatrix}$$
Where \( r_{ij} \) is the coordinate transformation matrix elements, \( r_{ij} \) is the element of the \( i \)th row, the \( j \)th column. \( p_{1x}, p_{1y} \) is the vector \( O_1O_j \) coordinates under coordinate system \( O_{1-xyz} \).

The compliance models of the amplifier and parallel plate

Compared with the lever amplifying mechanism, the bridge amplifying mechanism has better performance. So the bridge amplifying mechanism is selected as the \( P \) hinge of CTMP, which is shown in Figure 7. Because of the symmetry of the bridge amplifier, the analysis process can be simplified. Taking the left half as an analysis object, the point \( E \) is connected to the fixed ground through hinges 1, 2 in series and hinges 3, 4 in series, the two branches are in parallel. The compliance of the left half part at point \( E \) can be derived by:

\[
_{1}C_{E} = T^{E}_{o1}C_{o1}(T^{E}_{o1})^{T} + T^{E}_{o2}C_{o2}(T^{E}_{o2})^{T}
\]

\[
_{2}C_{E} = T^{E}_{o3}C_{o3}(T^{E}_{o3})^{T} + T^{E}_{o4}C_{o4}(T^{E}_{o4})^{T}
\]

\[
_{\text{one}}C_{E} = (_{1}C_{E})^{-1} + (_{2}C_{E})^{-1}
\]

In the same way, the compliance of the right half part at point \( E \) can be obtained:

\[
_{\text{two}}C_{E} = R(\pi)_{\text{one}}C_{E}(R(\pi))^{T}
\]

Where \( R(\pi) \) is the compliance transformation that around \( y \) axis of point \( E \) rotate 180°.

Because of the symmetry of the bridge amplifier, the compliance of the amplifier at point \( E \) can be derived by:

\[
C_{E} = ((_{\text{one}}C_{E})^{-1} + (_{\text{two}}C_{E})^{-1})^{-1}
\]

As shown in Figure 8, the compliance of the parallel plate can be derived by:

\[
C_{A} = \begin{bmatrix}
\frac{4\theta}{E\nu w} & 0 & -\frac{4\theta}{E\nu w} \\
0 & \frac{1}{E\nu w} & 0 \\
-\frac{4\theta}{E\nu w} & 0 & \frac{12l}{E\nu w}
\end{bmatrix}
\]

Where \( E \) is the material elastic modulus; \( w \) is the width of the flexible structure; \( t \) is the thickness of the flexible structure; \( l \) is the length of linkage.

The output compliance model

As shown in Figure 4, the output compliance is defined as the compliance at the point \( O \) (the center of the moving platform), where the external force is exerted, is related to the ground. Because of the double symmetric property, we only select the limb down left for the purpose of compliance model analysis.
\[ C_{\text{downleft}} = C_A^E + C_A^O \]
\[ C_{\text{down}} = (C_{\text{downleft}}^{-1} + C_{\text{downright}}^{-1})^{-1} \]

Accordingly, the compliances of limb left, right, and top can be derived. The output compliance of the \( XY \) stage can be calculated by:
\[ XYC_O = ((C_{\text{down}})^{-1} + (C_{\text{top}})^{-1} + (C_{\text{left}})^{-1} + (C_{\text{right}})^{-1})^{-1} \]

In the same way, the output compliance of the \( Z \) stage can be calculated by:
\[ ZC_O = ((C_E^O)^{-1} + (C_E^O)^{-1})^{-1} \]

**Performance analysis**

**Material selection**

The compliant micromanipulation based on the elastic deformation of the flexible hinge to achieve high precision movement, so the material mechanics performance requirements are higher.

The material for the \( XYZ \) CTMP is chosen to be an aluminum alloy, AL7075-T6, due to the material’s high \( \sigma_s/E \) ratio, low internal stresses, good strength, and long term phase stability, which makes it suitable for precision engineering applications. The attributes of this material are as follows Table 1.

**Strain and deformation**

The strain and deformation results reflect the performance of compliance, sensitivity, linearity, and verify the motion of the proposed CTMP. A set of selected piezoelectric linear actuators generate a representative force of 25 N on \( X \) axial of the mechanism in Figure 9. It can be observed that the maximal elastic strain with

![Figure 9](image-url)
When three set of piezoelectric actuators are acted on \( X/Y/Z \) with 25 N force respectively, similarly with the preceding situation, the total deformation and elastic strain is illustrated in Figure 10. It can be found that the maximal elastic strain is \( 3.03 \times 10^{-4} \text{ mm/mm} \). Besides, the moving platform is the maximal deformation with 16.96 \( \mu \text{m} \).

It is shown that the \( X \)-axis load–displacement curves basically satisfy the linear relationship under the load condition \( A \) or \( B \), a varied \( X \)-actuation range is over 0–100 N and a zero \( Y/Z \)-actuation (condition \( A \)) or a 25 N \( Y/Z \)-actuation (condition \( B \)), as shown in Figure 11. It can be seen that the load–displacement relationships for the CTMP can be regarded as linear under the two different load conditions. Based on finite element analysis, when the maximum output displacement (100 \( \mu \text{m} \)) is given in the direction of \( X/Y/Z \), the maximum allowable stress of CTMP is 213 MPa, which less than the allowable stress of the material.
Cross-axis coupling

The output-displacement coupling error EX (the displacement fluctuation of motion stage along $Y$ ($EX_y$) or $Z$ ($EX_z$) axis caused by $X$-actuation), EZ (the displacement fluctuation of motion stage along $X$ ($EZ_x$) or $Y$ ($EZ_y$) axis caused by $Z$-actuation) is shown in Figure 12 reflecting the cross-axis decoupling. It can be seen that the maximum coupling error of the CTMP is 2.743 $\mu$m. We can calculate that the maximum compared with coupling error is 2.52% at $EZ_x$. It is slightly larger than that we expect (According to the preview research, the cross-axis coupling of the initial $XY$ compliant platform in $XY$ axial is about 4.2%). This may be mainly caused by the deformation or gravity of platform.

Experimental verification

Experimental scheme design

This system includes micro-platform, PZT, PZT driving power, capacitive displacement sensor, DC power, PCI6221, and PC, as shown in Figure 13. We know that the PZT actuator has instinctive complex nonlinear phenomena. So we designed a nonlinear control systems based on the EUPI controller to reduce the complex complex hysteresis phenomena (It’s the result of my previous research.). The MATLAB simulink schematic is shown as in Figure 14.
Discussions of experimental results
As shown in Figure 14, when the PZT driver micro-positioning platform of nonlinear control systems added the step signal (Just consider the \( Z \) motion), so we completed the nonlinear composite closed-loop control to the platform, we can get the tracking performance and tracking error as shown in Figure 15, and we know that the system of the step signal average tracking error is only 1.43%.

As shown in Figure 14, when the PZT driver micro-positioning platform of nonlinear control systems added a sine wave signal \((30 \sin(2\pi t/50) + 30)\), so we completed the nonlinear composite closed-loop control to the platform, we can get the tracking performance and tracking error as shown in Figure 16, and we know that the system of a sine wave signal average tracking error is about 7.17%.

Conclusions
In this paper, an improved \( XYZ \) CTMP has been developed and tested. Compared between the original \( XY \) CTMP design and the improved design, we can find that the improved design have a higher degree of cross-axis decoupling with cross-axis coupling error (2.52%) less than the original \( XY \) CTMP (4.2%). Through nonlinear closed-loop control based on the EUPI controller, tracking error of \( XYZ \) CTMP is only 7.17%. The reason why the error is still large is that the filtering ability of capacitance displacement sensor is not enough. But the improved \( XYZ \) CTMP have convincing performance by FEA and experiment analysis. It provides a reference for the research of micro-platform.

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