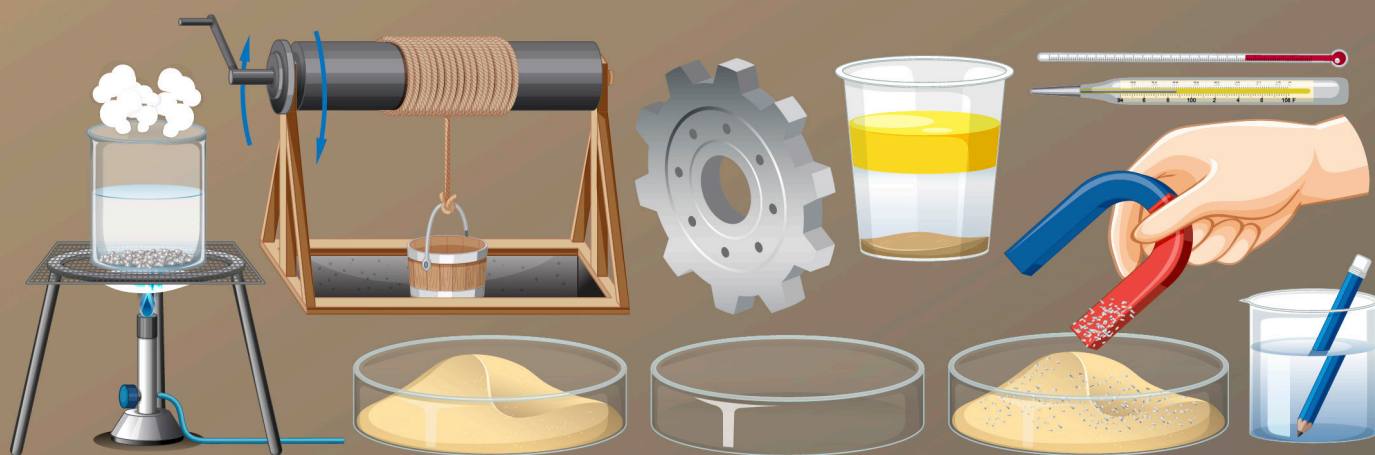




American Journal of Advanced Materials Research (AJAMR)

ISSN: 3070-2011 (ONLINE)

VOLUME 2 ISSUE 1 (2026)



PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Design and Analysis of 2-DOF Flexure Based Micromanipulator with Bridge Type Amplifier

Abdullah Al Fuad^{1*}, M.A. Shadab Siddiqui¹

Article Information

Received: July 29, 2026

Accepted: October 13, 2026

Published: October 29, 2026

Keywords

*Finite Element Analysis,
Flexure-Based Micromanipulator,
Mechanism Optimization, Precision
Positioning Application*

ABSTRACT

A new compliant parallel micromanipulator (CPM) with two degrees of freedom (2-DOF) and flexure joints with bridge-type displacement amplifier are proposed to micromanipulate. It is based on 2-DOF translational and amplification mechanism which adopts the flexure hinge to replace the traditional hinge. This monolithic mechanism provides 2 translational axes and having high frequency. Because of being precise in deformation, circular flexure hinges are adopted in the mechanism. FEA model is developed to perform to analysis and predict the behavior of this mechanism. In this way, computational Jacobian, workspace and amplification ratios are derived. The calculation of safety factor is used to explore the stress-strain relationship. Further, the output displacements, such as, equivalent stress, are computed on the input displacements of the different flexure radius and shapes. Geometrical modelling is determined. Result shows that compliant parallel micromanipulator's workspace is obtained $\pm 191.81 \mu\text{m} \times \pm 192.41 \mu\text{m}$. Analytically and computationally amplification ratios are 6.77 and 6.19 respectively. Natural frequency was found 2134 Hz and validated by analytically. This is a 2-DOF mechanism that reduces parasitic motion. Designing it is easy. Stiffness in output and output displacement are good.

INTRODUCTION

The components of flexure-based compliant manipulators are found to be more advantageous than classical joint mechanisms because of zero backlash, zero friction and being vacuum-compatible because the motion and forces are transduced using elastic deformations (Takosoglu *et al.*, 2023). This provides greater rigidity and precision when compared to classical revolute, prismatic or spherical joints. Compliant manipulators can fit into high-precision applications, such as optical fiber alignment, atomic force microscopy, microsurgery, and micromanipulation, because their small size and ability to make large strokes allow this (Alonso-González *et al.*, 2020).

They may be organized in serial or parallel with the serial design giving rise to 1-DOF mechanisms and the parallel design offering high accuracy, stiffness and load capacity (Liu *et al.*, 2022). Decoupled designs are easy to control and isolation safeguard the actuators against parasitic motions, which cut down on precision (Berendsen *et al.*, 2023). Flexure hinge micromanipulators can provide ultra-high precision in a variety of applications based on the idea that smooth, elastic motion can be used in place of mechanical joints that generate friction (Fan *et al.*, 2021). Piezoelectric actuators are able to achieve nanoscale precision but with low stroke, compared to voice coils that are more capable of motion but with lower force. This machine was able to shoot even a three-pound concrete ball a distance over 200 yards (Sasaki *et al.*, 2023). Constrained directions are described as Degrees of Constraint (DOC) and unrestrained directions are described as Degrees of Freedom (DOF). In Fig 1 conventional constraint elements have been shown.

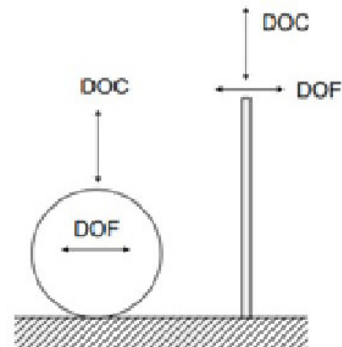


Figure 1: Example of conventional constraint elements (Zhou & Yan, 2023)

On a broad basis, the flexure hinges can be classified into two types; primitive flexure hinges and complex flexure hinges (J. Wang *et al.*, 2020). In general, flexure manipulators take advantage of elastic deformations in order to manipulate without friction with precision. K is the stiffness matrix and C is the compliance matrix, C and K are inverses. The flexure compliance matrix (right angle) is expressed in the following manner:

$$C = \begin{bmatrix} \frac{l}{Ebt} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{4l^3}{3Ebt^3} + \frac{l}{Gbt} & 0 & 0 & 0 & \frac{6l^2}{Ebt^3} \\ 0 & 0 & \frac{4l^3}{3Ebt^3} + \frac{l}{Gbt} & 0 & \frac{-6l}{Ebt^3} & 0 \\ 0 & 0 & 0 & \frac{l}{Gk_2bt^3} & 0 & 0 \\ 0 & 0 & \frac{-6l^2}{Ebt^3} & 0 & \frac{12l}{Ebt^3} & 0 \\ 0 & \frac{6l^2}{Ebt^3} & 0 & 0 & 0 & \frac{12l}{Ebt^3} \end{bmatrix} \quad [10]$$

¹ Department of Mechanical Engineering, Chittagong University of Engineering and Technology, Bangladesh

* Corresponding author's e-mail: abdullah.fuad65@gmail.com

Stiffness matrix, $K=C-1$

Development of micromanipulators involves systematic testing and evaluation for applications from industrial robots to microsurgery tools. (Dwarshuis, 2022) Compliant mechanisms provide advantages like high stiffness, accuracy through eliminating friction and backlash, and lower cost compared to traditional joints. (Yang *et al.*, 2022) However, limitations include inability to achieve continuous motion and stress concentration risks. (Hong *et al.*, 2022) Previous studies on flexure-based manipulators analyzed parasitic motion reduction, increased stiffness, decoupling and workspace enhancement through optimization, but achieved output displacement did not match expected values in some cases. (Huang *et al.*, 2023) New designs incorporated methods like topology optimization, hysteresis modeling, and asymmetric amplification to maximize performance metrics. (Li *et al.*, 2022) Most utilized piezoelectric actuation but voice coils provide greater motion range at the cost of force ability. Research gaps consisted of the limitation to parasitic motion in the multi-DOF design, and the loss in the displacement caused by the load (Chen & Lai, 2022). The aim of this paper is to solve these challenges by designing a new 2-DOF parallel flexure micromanipulator with voice coil operation, performing a series of static, dynamic, and stress analysis simulations to typify workspace, stiffness, natural frequency and displacement amplification used in robotic jobs that demand accuracy and precision positioning.

This paper seeks to design a new 2-DOF flexure-based micromanipulator with the following goals: attaining translational X -Y motion, workspace revelation, high resonant frequency, low parasitic motion, dynamics discovery through simulation, amplification ratio determination, analytically and by FEA, and flexure stiffness (Kloub, 2020). The non-linear behaviour of complex flexure combinations, fatigue problems and the available limited motion pose a challenge. Compared to conventional joints, compliant mechanisms have the benefits of high stiffness, no friction or backlash, reduced cost and increased efficiency (Yan *et al.*, 2022). Limitations though are inability to get constant motion, risk of stress concentration, and wear through cyclic loading (Eugster *et al.*, 2022). This research scope is to devise a type of mechanism that has the capability of precise positioning exploiting flexure mechanics and surmounting shortcomings of joint-based approaches including errors and friction to add to the applications of micro-manipulation in the future.

MATERIALS AND METHODS

The paper has developed and modeled a 2-DOF monolithic parallel flexure-based high-frequency micromanipulator based on simulation. CAD software was used to design the 3D model and structural analysis was done to compute workspace range, rotational stiffness, output stiffness and displacement (Kuang *et al.*, 2022). The stability of the structure was examined using

Stress analysis and dynamic modelling. Fig. 2 illustrates the CAD model of the micromanipulator which indicates different parts of the model in 3D view. The amplification process of Bridge type amplifier is displayed in Fig. 3

CAD Model of Mechanism Using Software

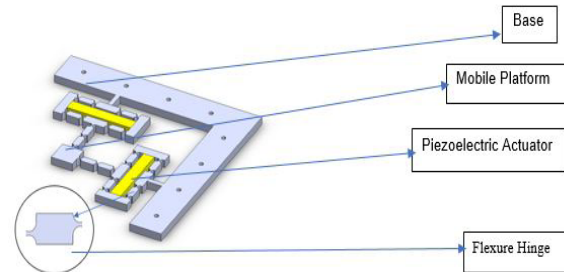


Figure 2: Monolithic 2-DOF micromanipulator model in 3D view.

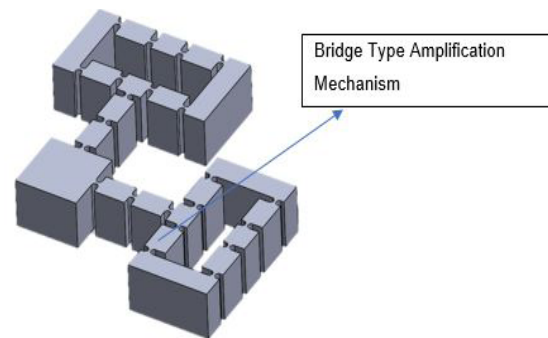


Figure 3: Kinematic chain of micromanipulator.

Mechanical Design Of 2-DOF Mechanism

Two bridge-type amplification mechanisms connected perpendicularly to flexure hinges built into an in-plane XY micropositioning stage make up this mechanism. Piezoelectric stacks have their motion transferred to the mobile platform by the flexure-based kinematic chains when actuated. The volumetric actuator (SA050520) offers 31 μm force and 900 N force at the desired range and resolution. The best displacement accuracy and least parasitic motion is achieved with right circular flexures (W. Zhang *et al.*, 2021). The kinematic modelling of the Bridge type of amplification mechanism is shown in Fig. 4.

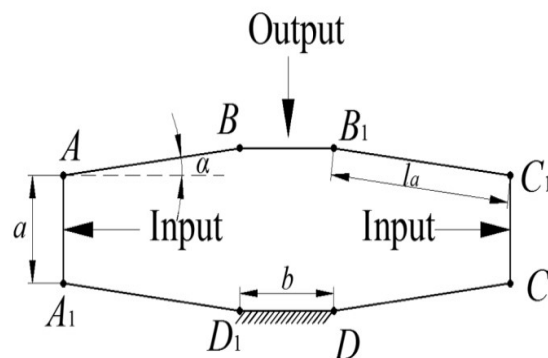


Figure 4: Kinematic chain of micromanipulator.

$$C = \frac{9\pi r^{0.5}}{2Ebt^{2.5}} \quad (1)$$

Where,

E= Young's modulus

w=Thickness

t= Critical thickness

r= Radius of circular flexure hinges

L= Distance between two adjacent hinge

Finite Element Analysis

FEA is used to address engineering problems with the help of software such as ANSYS that allows you to use modelling, optimization and analysis to solve problems in a static, transient and dynamic form (Liao *et al.*, 2022). ANSYS employs the use of methods like the static load steps, the Newmark integration, Newmark Newton-Raphson iteration procedures to find solutions to nonlinear equilibrium equations over load increments (Su *et al.*, 2023). The contact analysis in ANSYS should only define relevant contact surfaces during penalty and Lagrange contact analysis. Flexure-based mechanism has been demonstrated by Finite Element Analysis, which has been shown in Fig.5.

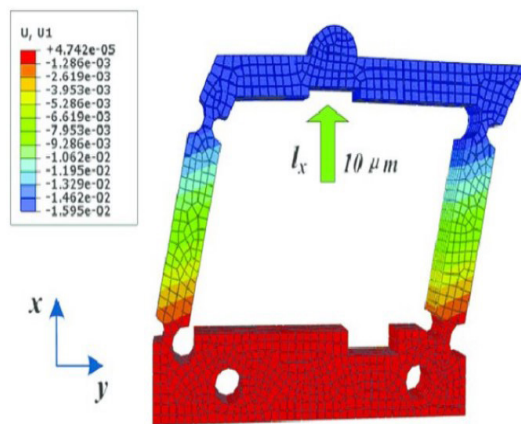


Figure 5: Finite element method

Material Selection

Table 1: Al 7075-T6's material properties

Properties	Values
Density	2810 kg/m ³
Modulus of Elasticity	70.7 GPa
Poisson's Ratio	0.33
Bulk Modulus	70.29 GPa
Shear Modulus	26.955 GPa
Tensile Yield Strength	503 MPa
Compressive Yield Strength	503 MPa
Tensile Ultimate Strength	572 MPa
Shear Strength	333 MPa

Geometrical Model of The Micromanipulator

The geometrical modelling of the micromanipulator is shown in Fig. 6. It is needed in determining design parameters of the manipulator. Fig. 7 illustrates the design of variances of shapes of flexure hinge and prismatic joint.

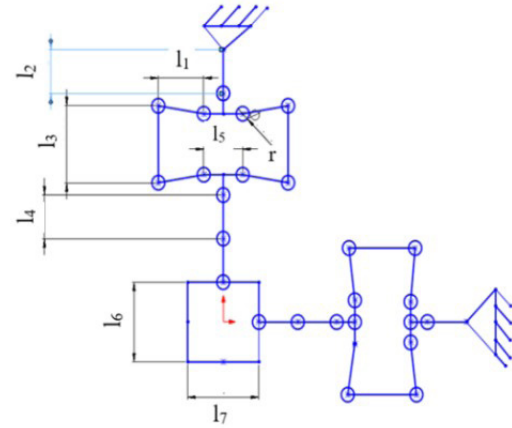


Figure 6: Geometrical model of the micromanipulator.

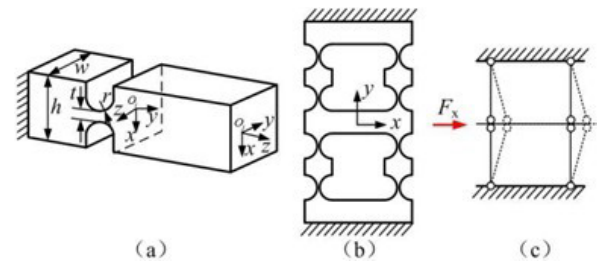


Figure 7: (a) Design of flexure hinge. (b) Prismatic joint (D. Zhang *et al.*, 2021)

Table 2: Design Parameters (mm)

11	12	13	14	15	16	17	r	t	b
7.01	5.98	10.60	6	6	11	11	1	0.4	6.5

Meshing

The 3D models drawn in SOLIDWORKS were meshed in ANSYS. The meshed models are shown in Fig 8 below. Element size was Fine (1 mm) and Span Angle Center was Fine. Element number 41041 number of nodes 203213. Fig. 8 illustrates FEA Meshing that is necessary.

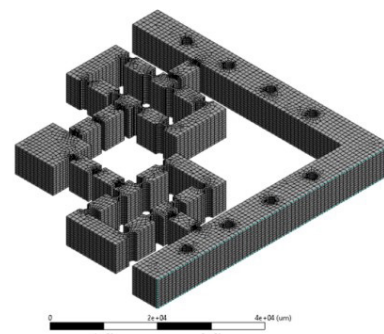


Figure 8: Mesh of the micromanipulator

Boundary Conditions

Boundary condition is needed before simulation of this study. Necessary boundary condition was applied which is shown in Fig 9. 8 holes in the base were supported in a fixed manner. In bridge type mechanism input displacement was used (Chang *et al.*, 2022). The displacement of amount of input along 2 direction was 31 μm in each mechanism of the bridge.

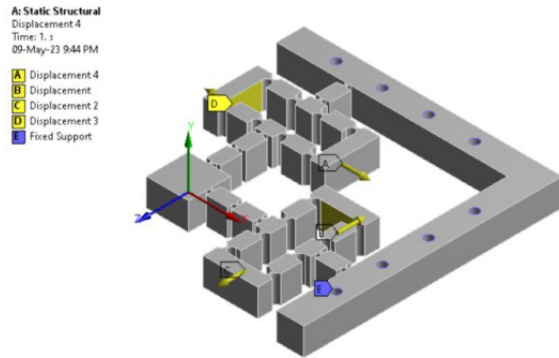


Figure 9: Boundary Condition Applied for Simulation.

Selected Piezoelectric Actuator

This mechanism was chosen based on dimension and select a piezoelectric actuator model SA050520. It is 5 mm×5 mm×20 mm in size. It has a voltage of 150 V, a capacitance of 1.8 Umu and a stiffness of 41 N/mm. It has input displacement range of 31 μm and force of 900 N.

RESULTS AND DISCUSSION

Displacement Amplification Ratio

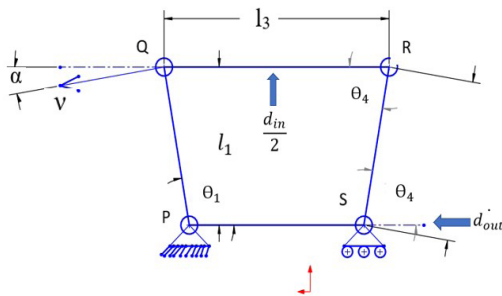


Figure 10: Four-bar mechanism

The displacement amplification ratio can be obtained as follows:

$$r_{amp} = -\frac{1}{\sin\alpha} \left\{ \cos\theta_1 + \frac{\sin\theta_2}{l_{RS}\sin\theta_3} (l_{QR} + l_{RS}\cos\theta_3) \right\} \quad (2)$$

From Eq. (2), $r_{amp}=6.77$

Table 3: Comparison between analytical and FEA method

Input	Analytical	FEA	% of error
X	6.77	6.19	8.57%
Y	6.77	6.187	8.61%

Total Deformation

Elastic deformation of flexure parts is essential in determining the total deformation of a flexure-based

mechanism that is important in design and optimization (Pham *et al.*, 2023). This may cause repeatability, loss of accuracy, malfunction due to excessive deformation and reliability. Fig. 11 shows that the total deformation of a mechanism was 194.96 μm .

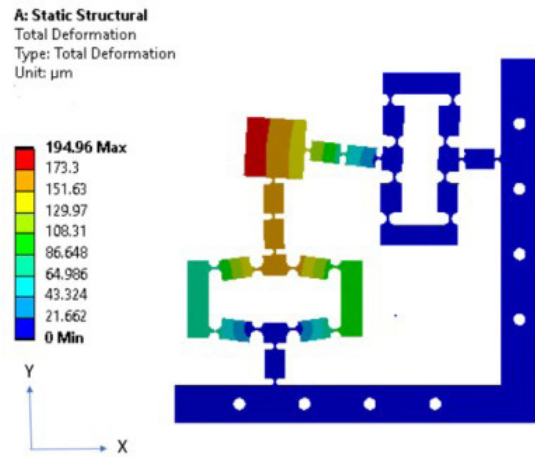


Figure 11: Total deformation

Equivalent (Von-Mises) Stress

Identical von-Mises stress measures stress condition in a system of flexure, in terms of magnitude and distribution (Bhoyar *et al.*, 2020). It evaluates the life of machine in the presence of fatigue by estimating the maximum stress experienced by flexure members under cyclic load. FEA was used to compute the stress of 297.64 MPa as indicated in Fig. 12.

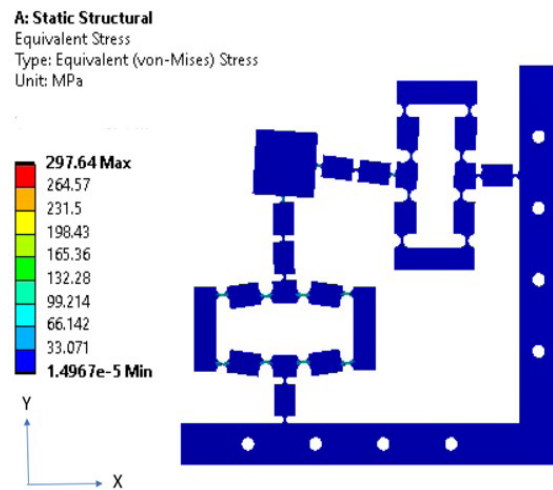


Figure 12: Equivalent (von-Mises) stress

Directional Deformation:

Achieving desired motion or force transmission in a flexure-based mechanism is dependent upon directional deformation (Y. Wang *et al.*, 2022). This allows engineers to design optimally to minimize stress concentrations, enhance accuracy and repeatability, to make the mechanism operate reliably with the expected life cycle. Gathering the directions of deformations of the micromanipulator along X and Y in Fig. 13, the X and Y deformations are 191.81 0 and 192.41 0, respectively.

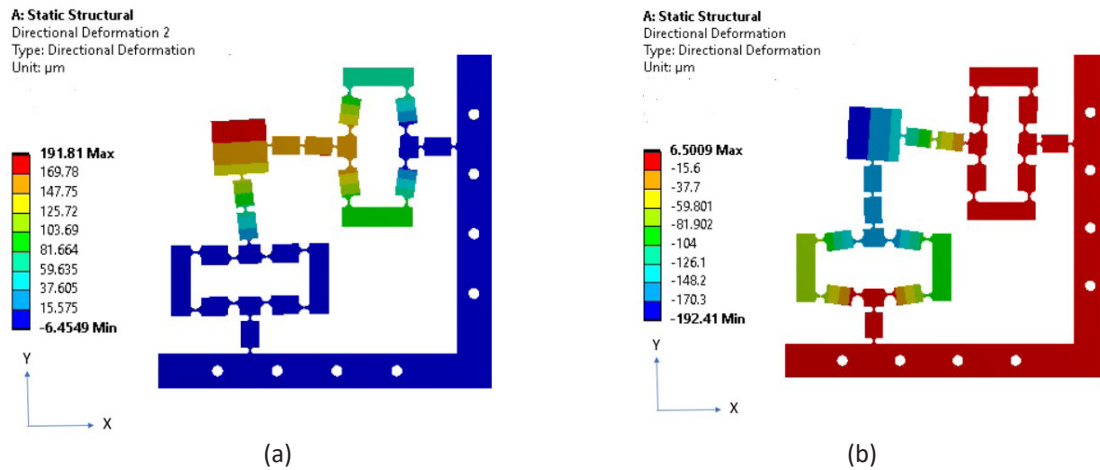


Figure 13: (a) Directional deformation along X axis (b) Directional deformation along Y axis

Input Displacement Vs Output Displacement And Amplification Ratio

The geometry and mechanical properties affect the input and output displacement of the circular flexures. For a given input displacement, the flexure's stiffness affects the output displacement. The stiffer it is, the smaller the radius and the thickness (Bian & Wang, 2020). The

changes in the output displacement of different input displacement and amplification ratios are indicated in Table 4. Fig. 14 gives the output displacement versus the input displacement of a circular flexure of radius 1 mm. The input displacement is plotted at the X-axis; the output displacement is plotted at Y.

Table 4: Input Displacement, Output Displacement & Amplification Ratio

Input Displacement (μm)	Output Displacement (μm)	Amplification Ratio
5	31	6.2
10	62	6.2
15	94.33	6.2
20	125.78	6.2
25	157.22	6.2
30	188.67	6.2

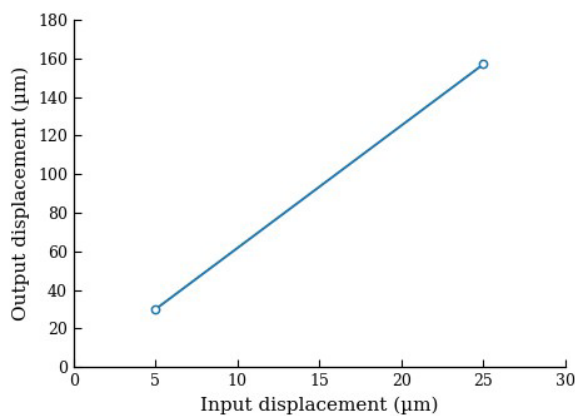


Figure 14: Output Displacement Vs Input Displacement

Output Displacement Vs Input Displacement for Circular Flexure (Radius= 2mm)

Table 5 shows variation of output displacement for different input displacement and amplification ratio for circular flexure of radius 2 mm. Fig 15 represents output displacement vs input displacement for circular flexure of radius 2 mm. Along X axis, input displacement and Y axis, output displacement are represented

Table 5: Input displacement, output displacement & amplification ratio

Input Displacement (μm)	Output Displacement (μm)	Amplification Ratio
5	27.43	5.49
10	54.86	5.49
15	82.29	5.49
20	109.72	5.49
25	137.15	5.49
30	164.58	5.49

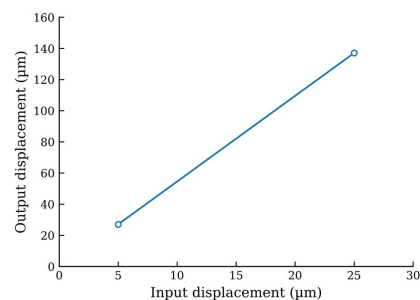


Figure 15: Output Displacement Vs Input Displacement

FEA Analysis Using Leaf Flexure

Leaf flexures This is a simple, high-strength flexure mechanism that employs thin and flat leaf springs to provide an accurate, repeatable motion (or force) transfer. Their use has been popular because of their

high precision, friction and flexibility in direction and magnitude of motion (Jiang *et al.*, 2022). Fig. 16 shows directions of X and Y axis deformation of leaf flexure. It was found to be 210.62 μm and 211.08 μm respectively for input displacement of 31 μm .

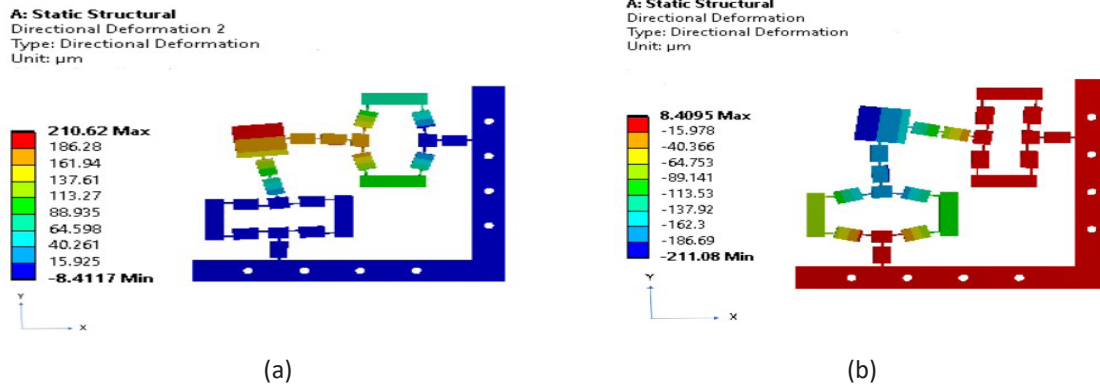


Figure 16: Directional deformation for leaf flexure. (a) Directional deformation along X axis (b) Directional deformation along Y axis

Equivalent (von-Mises) for leaf flexure is shown in Fig. 17 Maximum stress was found from simulation by FEA was 125.58 MPa for input displacement of 31 μm .

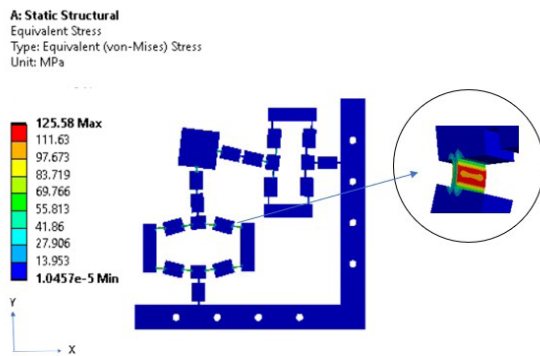


Figure 17: Equivalent stress for leaf flexure

Output Displacement Vs Input Displacement for Leaf Flexure

Table 6 illustrates the change of output displacement at different input displacement and amplification ratio of leaf flexure. Fig 18 is an output displacement versus input displacement of leaf flexure (Thalmann & Henein, 2022). Along X axis, input displacement and along Y axis, output displacement are represented. It portrayed linear relationship between them.

Table 6: Input displacement, output displacement & amplification ratio

Input Displacement (μm)	Output Displacement (μm)	Amplification Ratio
5	34.44	6.89
10	68.89	6.89
15	103.33	6.89
20	137.77	6.89
25	172.22	6.89
30	206.66	6.89

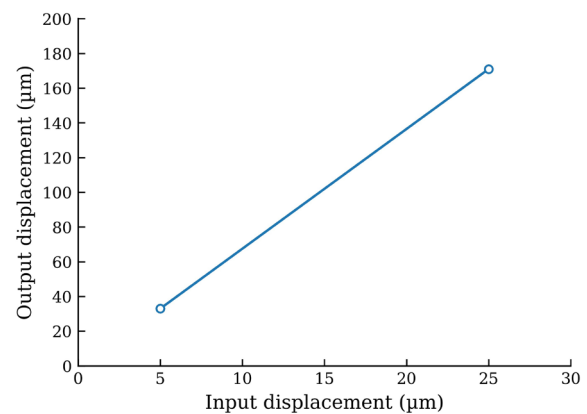


Figure 18: Output Displacement Vs Input Displacement for Leaf Flexure

Workspace

A 2 DOF flexure-based micromanipulator's workspace is the area that the end effector can access while it is moving in all directions. This is influenced by the geometry, mechanical properties and the range of actuators. The FEA model can be used to calculate the output displacements.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} d_{PEA1} \\ d_{PEA2} \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} X \\ Y \end{bmatrix} = J_{com} \begin{bmatrix} d_{PEA1} \\ d_{PEA2} \end{bmatrix}$$

Jacobian matrix for workspace (3)
dPEA1 and dPEA2 are the input displacements of PEA1 and PEA2 respectively. The letters X and Y respectively represent the appropriate output displacements of Motion Stage in X and Y directions respectively. Jcom is the ratio of the kinematic matrix of the designed mechanism to the displacement.
By solving Jacobian matrix,

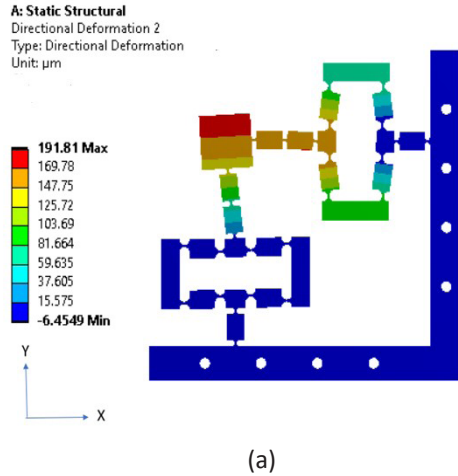
$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} -6.16 & 0.027 \\ -0.085 & 6.219 \end{bmatrix} \begin{bmatrix} 31 \\ 131 \end{bmatrix}$$

X = -190.12 μm , Y = 190.154 μm .

It depicts the movement of the motion stage along the X and Y axes when the input displacements for PEA1 and PEA2 were changed from 0 to 31 m.

The equation (2), which represents the quantity of input displacements in both bridge type mechanisms, was used to derive the inverse kinematics of this mechanism. A

$$\begin{bmatrix} dPEA1 \\ dPEA2 \end{bmatrix} = J_{com}^{-1} \begin{bmatrix} X \\ Y \end{bmatrix} \quad (4)$$



Here, J_{com}^{-1} is the inverse kinematic matrix representing displacement amplification ratio.

From Eq (3), the inverse kinematic matrix was, Eq (4),

$$J_{com}^{-1} = \begin{bmatrix} -0.1623 & 0.0007 \\ -0.0022 & 0.1608 \end{bmatrix}$$

Determination of Workspace using FEA

In Fig. 20 workspace was calculated. Along X direction it was found -191.81 μm and along Y direction it was found 192.41 μm .

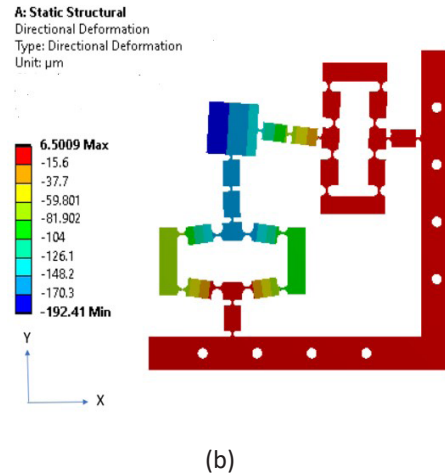


Figure 19: Workspace Using FEA, (a)Along X Direction It Was Found -191.81 μm (b)Along Y Direction It Was Found 192.41 μm .

Rotational Stiffness

$$\text{Rotational stiffness, } k_{\theta} = \frac{2Ebt^{2.5}}{9\pi R^{0.5}} \quad (5)$$

$$\text{From Eq. (5), } k_{\theta} = 104.17 \frac{\text{N}}{\mu\text{m}}$$

Dynamic Modelling

The natural frequency of the micromanipulator can be derived using the Lagrange equation:

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = F_i \quad (6)$$

where the kinetic and potential energies of the mechanism are T and V, respectively, and is the generalized non-conservative force.

The motion of the linkage of the micromanipulator and piezoelectric actuation at the input ends of the mechanism's kinetic energy can be expressed as follows:

$$T = \frac{1}{2} m_A \dot{d}_{out}^2 + \frac{1}{2} m_c \left\{ \left(\frac{\dot{d}_{in}}{2} \right)^2 + \left(\frac{\dot{d}_{out}}{2} \right)^2 \right\} \times 2 + \frac{1}{2} m_B \left\{ \left(\frac{\dot{d}_{in}}{4} \right)^2 + \left(\frac{3\dot{d}_{out}}{4} \right)^2 \right\} \times 4 + \frac{1}{2} I_B \dot{\theta}_B^2 \times 4 + \frac{1}{2} m_D \left\{ \left(\frac{\dot{d}_{in}}{4} \right)^2 + \left(\frac{\dot{d}_{out}}{4} \right)^2 \right\} \times 4 + \frac{1}{2} I_D \dot{\theta}_D^2 \times 4 \quad (7)$$

Where m_A , m_B , m_C , m_D are mass of the input end, the output end, and the connecting links as shown in Fig. 1B and ID are the second moment of inertia of the mass of the link B and D. Substituting the $d_{out} = \text{rampdin}$ and $\theta_B = \theta_D = d_{out}/2L$, the kinetic energy can be derived as,

$$T = \frac{1}{2} m_A \dot{d}_{amp}^2 + 2m_B \left(\frac{1}{16} + \frac{9}{16} r_{amp}^2 \right) \dot{d}_{in}^2 + \frac{1}{12} m_B r_{amp}^2 \dot{d}_{in}^2 + m_c \left(\frac{1}{4} + \frac{1}{4} r_{amp}^2 \right) \dot{d}_{in}^2 + 2m_D \left(\frac{1}{16} + \frac{1}{16} r_{amp}^2 \right) \dot{d}_{in}^2 \quad (8)$$

The potential energy of the mechanism due to elastic deformation of the flexure hinges can be expressed by:

$$V = 8 \times \frac{1}{2} k_{\theta} (\theta_B^2 + \theta_D^2) \quad (9)$$

The equivalent mass and stiffness can be calculated by substituting the kinetic and potential energy equation from equations (15) and (16) into equation (13), as shown below.

$$M = m_A r_{amp}^2 + 4m_B \left(\frac{1}{16} + \frac{9}{16} r_{amp}^2 \right) + \frac{1}{16} m_B r_{amp}^2 + 2m_c \left(\frac{1}{4} + \frac{1}{4} r_{amp}^2 \right) + 4m_D \left(\frac{1}{16} + \frac{1}{16} r_{amp}^2 \right) \\ K = \frac{4k_{\theta} r_{amp}^2}{L^2} \quad [5] \quad (10)$$

The natural frequency of the micromanipulator can be derived by:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K}{M}} \quad (11)$$

Equivalent mass, $M = 0.200967 \text{ Kg}$.

Stiffness, $K = 36.1 \text{ N}/\mu\text{m}$.

Natural frequency, $f_n = 2133.10 \text{ Hz}$.

Modal Analysis

By replacing equation (10) and (11) kinetic and potential energy equation with equation (8) the equivalent mass and stiffness can be determined as follows. Two Mode shapes were the description of two natural frequencies in two directions. There are two mode shape as shown in Fig. 21 along X and Y axis, natural frequency was determined as 2134 Hz that is nearly equal to the analytical result 2133 Hz.

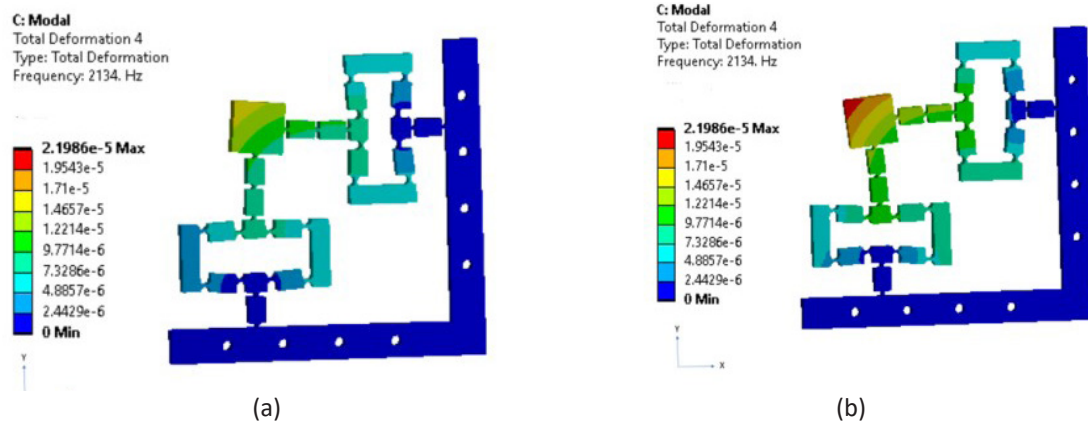


Figure 20: Modal Analysis Of The Micromanipulator. (a) Natural Frequency Along X Axis. (b) Natural Frequency Along Y Axis

Table 7: Comparison between analytical and FEA method

Input	Analytical	FEA	% of error
X	2133	2134	0.0468%
Y	2133	2134	0.0468%

Output Stiffness of The Mechanism

Required reaction force calculating rotational stiffness has been displayed in Fig. 22.

Stiffness of the mechanism was calculated from,

$$F = k \times x \quad (12)$$

Where, F = Reaction force of the motion stage, k = Output stiffness of the mechanism, x = Total deformation.

Output stiffness,

$$k = \frac{F}{x} = \frac{176.77}{237.71} = 0.74 \text{ N}/\mu\text{m}$$

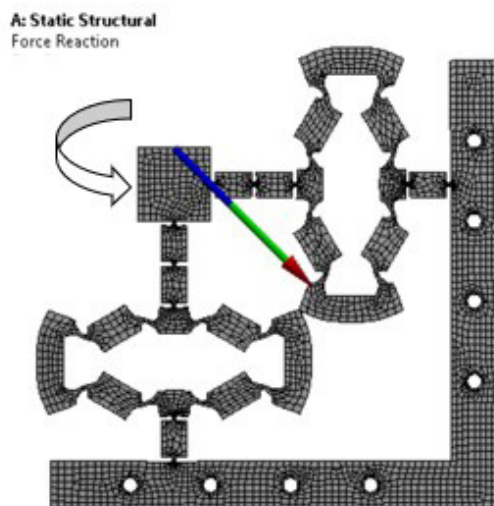


Figure 21: Reaction Force of The Mechanism

Safety Factor

A Safety Factor (FOS) is a safety margin in mechanical design of structures (especially flexural-based mechanisms). It is computed by dividing the ultimate strength of the material to the load applied calculated

using analytical or numerical tools such as finite element analysis.

$$\text{Safety factor} = \frac{\text{Yield Strength}}{\text{Tensile Strength}} = \frac{503}{373.32} = 1.35$$

Input Stiffness

From Eq (18), input stiffness $k_{in} = 6.2 \text{ N}/\mu\text{m}$.

$$k_{in} = \frac{2Ebt^3}{l(t^2 \cos^2 \theta + l^2 \sin^2 \theta)} \quad [6] \quad (13)$$

With FEA the paper studied the deformation in total of the 2-DOF with one mm-radius bending around a circular. They found that the input displacement was directly proportional to the output displacement and the ratio of the amplification was found to be 6.2. The errors calculated on X and Y were 8.57% and 8.61% respectively. Measurements of workspace, X and Y axis were determined as -191.81 mm and 192.41 mm, respectively and the output stiffness was 0.74 N/mm.

CONCLUSION

This paper introduced a 2-DOF parallel micromanipulator with natural frequency optimization which was analyzed by using computational analysis and modal testing. The mechanism possessed good dynamic nature with a natural frequency of 2134 Hz with low percentage error. The ratios of amplification were determined and confirmed by analytical and FEA. The stiffness of the output was 0.74 N/um and the safety factor was 1.35 which can be refined by designing the output. Another aspect of the study was the study of the relationship between output and input displacement which was found linear. The work in future will involve the use of parametric optimization, experimental research, and alternative actuators and methods to improve performance. The results pave the way to new opportunities of nanomanipulation and precision uses.

REFERENCES

- Alonso-González, E., Godínez-Bravo, R., Lara Chávez, J. A., & Magos-Rivera, M. (2020). Development of a 2-DOF mechanism for pick-and-place tasks. In *Proceedings of the 18th LACCEI International Multi-Conference for Engineering, Education, and Technology: Engineering, Integration, and Alliances for a Sustainable Development: Hemispheric Cooperation for Competitiveness and Prosperity on a Knowledge-Based Economy*. <https://doi.org/10.18687/LACCEI2020.1.1.599>
- Berendsen, D., Sridhar, A., & Aarts, R. (2023). A redundantly actuated 2-DOF 3RRR PKM with flexure joints: Less is more. *Multibody System Dynamics*, 59(1), 1–17. <https://doi.org/10.1007/s11044-023-09904-w>
- Bhoyar, S., Bhojwani, V., & Sanap, S. (2020). Parametric Design and Comparative Analysis of a Special Purpose Flexure Spring. *E3S Web of Conferences*, 170, 02013. <https://doi.org/10.1051/e3sconf/202017002013>
- Bian, B., & Wang, L. (2020). Design, Analysis, and Test of a Novel 2-DOF Spherical Motion Mechanism. *IEEE Access*, 8, 53561–53574. <https://doi.org/10.1109/ACCESS.2020.2981548>
- Chang, Y.-S., Kieu, V. N. D., & Huang, S.-C. (2022). Optimal Design of a Leaf Flexure Compliant Mechanism Based on 2-DOF Tuned Mass Damping Stage Analysis. *Micromachines*, 13(6), 817. <https://doi.org/10.3390/mi13060817>
- Chen, Y., & Lai, L. (2022). Design, Modeling, Testing, and Control of a Novel Fully Flexure-Based Displacement Reduction Mechanism Driven by Voice Coil Motor. *Actuators*, 11(8), 228. <https://doi.org/10.3390/act11080228>
- Dwarshuis, K. (2022). *Beam-based analysis of flexure mechanisms: Increasing computational efficiency, accuracy and design freedom* [PhD, University of Twente]. <https://doi.org/10.3990/1.9789036554831>
- Eugster, M., Merlet, J.-P., Gerig, N., Cattin, P. C., & Rauter, G. (2022). Miniature parallel robot with submillimeter positioning accuracy for minimally invasive laser osteotomy. *Robotica*, 40(4), 1070–1097. <https://doi.org/10.1017/S0263574721000990>
- Fan, W., Jin, H., Fu, Y., & Lin, Y. (2021). A type of symmetrical differential lever displacement amplification mechanism. *Mechanics & Industry*, 22, 5. <https://doi.org/10.1051/meca/2021003>
- Hong, Y., Wu, Y., Jin, S., Liu, D., & Chi, B. (2022). Design and Analysis of a Microgripper with Three-Stage Amplification Mechanism for Micromanipulation. *Micromachines*, 13(3), 366. <https://doi.org/10.3390/mi13030366>
- Huang, W., Lei, Y., An, D., Su, Y., & Liang, Z. (2023). Design and Analysis of a Novel 2-DOF Rotation–Translation Precision Positioning Stage. *Mathematics*, 11(2), 280. <https://doi.org/10.3390/math11020280>
- Jiang, J., Tan, Q., He, T., Sun, J., & Zhang, J. (2022). Safety Analysis, Design and Evaluation of 2-DOF Parallel Lifting Actuator on Stereo Parking Robot. *Actuators*, 11(7), 181. <https://doi.org/10.3390/act11070181>
- Kloub, H. (2020). Force Amplification Mechanism for Increased Stroke and Speed Responses of Piezoelectric Stick-Slip Miniaturized Linear Motor. *The 1st International Electronic Conference on Actuator Technology: Materials, Devices and Applications*, 17. <https://doi.org/10.3390/IeCAT2020-08518>
- Kuang, L., Marchal, M., Aggravi, M., Giordano, P. R., & Pacchierotti, C. (2022). Design of a 2-DoF Haptic Device for Motion Guidance. In H. Seifi, A. M. L. Kappers, O. Schneider, K. Drewing, C. Pacchierotti, A. Abbasimoshaei, G. Huisman, & T. A. Kern (Eds.), *Haptics: Science, Technology, Applications* (Vol. 13235, pp. 198–206). Springer International Publishing. https://doi.org/10.1007/978-3-031-06249-0_23
- Li, Z., Su, Z., Wang, H., Du, S., & Sun, H. (2022). Design and Locomotion Study of Two-DOF Actuator Driven by Piezoelectric–Electromagnetic Hybrid Mode. *Sensors*, 22(10), 3739. <https://doi.org/10.3390/s22103739>
- Liao, S., Ding, B., & Li, Y. (2022). Design, Assembly, and Simulation of Flexure-Based Modular Micro-Positioning Stages. *Machines*, 10(6), 421. <https://doi.org/10.3390/machines10060421>
- Liu, J., Luo, T., Liu, K., Lai, T., Zhao, Y., & Wang, L. (2022). A Novel Fast Servo Tool Device with Double Piezoelectric Driving. *Micromachines*, 14(1), 85. <https://doi.org/10.3390/mi14010085>
- Pham, H.-T., Nguyen, V.-K., Dang, Q.-K., Duong, T. V. A., Nguyen, D.-T., & Phan, T.-V. (2023). Design Optimization of Compliant Mechanisms for Vibration-Assisted Machining Applications Using a Hybrid Six Sigma, RSM-FEM, and NSGA-II Approach. *Journal of Machine Engineering*. <https://doi.org/10.36897/jme/166500>
- Sasaki, M., Muguro, J., Njeri, W., & Doss, A. S. A. (2023). Adaptive Notch Filter in a Two-Link Flexible Manipulator for the Compensation of Vibration and Gravity-Induced Distortion. *Vibration*, 6(1), 286–302. <https://doi.org/10.3390/vibration6010018>
- Su, S., Pham, D. T., Ji, C., Wang, Y., Huang, J., Zhou, W., & Wang, H. (2023). Design of a compliant device for peg-hole separation in robotic disassembly. *The International Journal of Advanced Manufacturing Technology*, 124(9), 3011–3019. <https://doi.org/10.1007/s00170-022-10573-w>
- Takosoglu, J., Janus-Galkiewicz, U., & Galkiewicz, J. (2023). A Design of a 2 DoF Planar Parallel Manipulator with an Electro-Pneumatic Servo-Drive—Part 2. *Energies*, 16(7), 2970. <https://doi.org/10.3390/en16072970>
- Thalmann, E., & Hencin, S. (2022). Triple Crossed Flexure Pivot Based on a Zero Parasitic Center Shift Kinematic Design. *Journal of Mechanisms and Robotics*, 14(4), 045001. <https://doi.org/10.1115/1.4053471>
- Wang, J., Zheng, Y., Li, J., Liu, C., Huang, Y., & Liu, Y. (2020). An Output Force Control for Robotic Manipulator by Changing the Spring Stiffness. *Mathematical Problems in Engineering*, 2020, 1–10. <https://doi.org/10.1155/2020/1489076>

- Wang, Y., Chen, J., & Qu, D. (2022). Design, Analysis and Experimental Investigations of a Double-Arm Based Micro-Gripper for Thin and Flexible Metal Wires Manipulation. *Micromachines*, 13(6), 925. <https://doi.org/10.3390/mi13060925>
- Yan, L., Jiang, A., Jiang, F., Liu, G., Wang, F., & Wu, X. (2022). Design and Performance Analysis of a Micro-Displacement Worktable Based on Flexure Hinges. *Micromachines*, 13(4), 518. <https://doi.org/10.3390/mi13040518>
- Yang, F., Zhao, Y., Li, H., Mu, X., Zhang, W., Yue, H., & Liu, R. (2022). Design and Analysis of a 2-DOF Electromagnetic Actuator with an Improved Halbach Array for the Magnetic Suspension Platform. *Sensors*, 22(3), 790. <https://doi.org/10.3390/s22030790>
- Zhang, D., Sun, Y., & Lueth, T. C. (2021). Design of a novel tendon-driven manipulator structure based on monolithic compliant rolling-contact joint for minimally invasive surgery. *International Journal of Computer Assisted Radiology and Surgery*, 16(9), 1615–1625. <https://doi.org/10.1007/s11548-021-02442-w>
- Zhang, W., Yuan, J., Yan, C., Gao, Z., & Dong, Y. (2021). Multi-Objective Optimization Design of Natural Frequency of Two-Degree-of-Freedom Fast Steering Mirror System. *IEEE Access*, 9, 33689–33703. <https://doi.org/10.1109/ACCESS.2021.3061473>
- Zhou, S., & Yan, P. (2023). Design and Analysis of a Hybrid Displacement Amplifier Supporting a High-Performance Piezo Jet Dispenser. *Micromachines*, 14(2), 322. <https://doi.org/10.3390/mi14020322>