Design and analysis of a flexure-based modular precision positioning stage with two different materials

Bingxiao Ding
Department of Electromechanical Engineering, University of Macau, Taipa, Macao

Yangmin Li
Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong and Tianjin Key Laboratory for Advanced Mechatronic System Design and Intelligent Control, Tianjin University of Technology, Tianjin, China, and

Xiao Xiao and Zhigang Wu
Department of Electromechanical Engineering, University of Macau, Taipa, Macao

Abstract

Purpose – Generally, the motion range of the micro scale operation is within several hundreds of microns, and the conventional joints cannot satisfy the requirements due to manufacturing and assembling errors, hysteresis and backlash in the joints. The paper aims to discuss these issues.

Design/methodology/approach – The following issues should be considered: a micromanipulation stage should be designed using a small-dimensional scale driven by the small size of piezoelectric actuator and the components can be replaced due to fatigue failure caused by repeated cyclic loading. This paper proposes a modular design of a flexure-based 2-DOF precision stage made using aluminum (T6-7075) material and Acrylonitrile Butadiene Styrene plastic material. The piezoelectric actuator is adopted to drive the stage for the fast response and large output force. To compensate the stroke of piezoelectric actuator, a bridge-type amplifier is designed with optimized structure.

Findings – The simulation results validate the advantages of modular positioning stage fabricated by two different materials.

Research limitations/implications – The stage can be used in micro scale precision’s applications. If it will be used in nanoscale precision, then some sensors in nanoscale of measurement should be used.

Practical implications – The designed stage can be used in biomedical engineering, such as cell injection testing, etc.

Social implications – The designed stage will be used in micro/nanoengineering field, such as micro/nanomanufacturing or assembly, manipulation of cell, etc., which will push forward high technology to a higher level.

Originality/value – Two kinds of materials have been selected to make the positioning stage, which are seldomly found in literature on compliant mechanism field. A modular design concept is proposed for the positioning stage design.

Keywords Modular design, Kinematic analysis, Flexure mechanism, Micro-positioning stage

Received 5 October 2016
Revised 29 November 2016
3 January 2017
14 February 2017
23 May 2017
Accepted 30 June 2017

This work is partially supported by National Natural Science Foundation of China (51575544), Tianjin Natural Science Foundation (16JCZDJC38000) and Research Committee of Hong Kong Polytechnic University (G-YZ1G, 1-ZE97).
1. Introduction

The 2-DOF flexure-based positioning stages with ultrahigh precision play an essential role in high-precision manufacturing machine and high-precision measurement instruments, such as atomic force microscopy (Schittera et al., 2008), nanoimprint lithography (Teo et al., 2014), precision machining and micro/nanomanipulation (Li and Xu, 2012a, b). Generally speaking, the motion range of the micro and nanoscale operation is within several hundreds of microns, and the conventional joints cannot satisfy the requirements due to assembling errors, hysteresis and backlash in the joints. To overcome these limitations, the monolithic flexure hinges are adopted as revolute joints to improve the motion accuracy for the advantages of no friction, no wear, no backlash and no need for lubrication (Ding and Li, 2014), (Goldfarb and Speich, 1999). The flexure-based mechanisms are capable of achieving highly precise positioning motion via flexure hinges, which can provide a smooth and continuous motion via elastic deformation.

Piezoelectric actuators are able to provide better resolution using closed-loop control method and have been extensively used in academia and industry, compared with voice coil motor, shape memory alloy and electromagnetic actuator, (Ang et al., 2007; Ding et al., 2016). The flexure-based positioning stages integrated with piezoelectric actuators have attracted much attention because of their remarkable performances and applications in bio-engineering and mechanical engineering field (Qi et al., 2015; Hao and Hand, 2016). However, the main disadvantage of the piezoelectric actuator is the limited output displacement, in order to compensate the output stroke of the piezoelectric actuator, the amplification mechanism is adopted which may reduce resolution of the stage. During the literature review, the lever amplification mechanism, Scott-Russell amplification mechanism and bridge-type mechanism are frequently adopted to amplify the stroke of the piezoelectric actuator (Yong et al., 2009; Tian et al., 2009; Li and Xu, 2012a, b). However, the aforementioned monolithic mechanism cannot change their amplification mechanisms for different requirements. Compared with the monolithic structure, the modular stage can use different types of amplifiers with different amplification ratios to replace the original amplifier mechanisms for different applications.

In this paper, a modular 2-DOF positioning stage fabricated with two different materials is proposed. Due to using two different materials, the required maximum stress and force loading on the flexure hinges caused by piezoelectric will decrease, so that the stage can be easily miniaturized, and high-output force piezoelectric elements are not needed.

The remainder of this paper is organized as follows: Section 2 briefly introduces motivations of this research; Section 3 describes the principle of the modular design in details; the simulation results and performance analysis are given in Section 4; and the conclusions are made in Section 5.

2. Motivations of the research

The traditional monolithic precision positioning stages are generally fabricated by aluminum alloy material using electrical discharging machining (EDM) method (Jung and Kim, 2014), (Qin et al., 2013). This kind of monolithic structure has the advantage of no assembling errors, however, disadvantages are time-cost manufacturing process and the failure components cannot be replaced. Moreover, the stiffness along the driven direction can lead to displacement loss. As shown in Figure 1, mechanisms are subjected to the same constraint conditions and the solid type Quad.4 with 182 node was chosen as the element to mesh the stage. The output displacement of Figure 1(a) (maximum 31.81 μm) is larger than Figure 1(b) (23.65 μm), which are both made by aluminum alloy material because the flexure guider’s stiffness has led to displacement loss. Figure 1(c) is the modular structure in which the amplification mechanism is made by aluminum alloy material, flexure guider is made by Acrylonitrile Butadiene Styrene (ABS) material and the maximum output displacement is 31.62 μm. It means that in order to achieve the same output displacement, the modular
mechanism with different materials requires less driven force than monolithic structure fabricated by aluminum alloy material. In other words, the piezoelectric actuator with high-output force is not necessary and is much easier to miniaturize the dimension scale of the stage. Moreover, different flexure hinges have different recycle life in the monolithic structure due to the repeated cyclic loading. Referring to the simulation results shown in Figure 2, the bridge-type amplifier mechanism will be broken first with the 15-μm input displacement. In this scenario, the loading ratio is \( R = 0 \) due to the property of piezoelectric actuators. It means that when applying an input displacement to the monolithic stage, the bridge-type amplification mechanism is much easier to be broken than flexure guider mechanism. For modular structure, each part can be replaced easily when one module fails to serve.

**Figure 1.**
Output displacement comparison under 10 N driven force

**Notes:**
(a) Simulation of bridge type amplifier at maximum deformation of 31.811 μm;
(b) simulation of bridge type amplifier with flexure guider at maximum deformation of 23.65 μm;
(c) output displacement simulation of assembled bridge amplifier and flexure guider at maximum deformation 31.624 μm

**Figure 2.**
Fatigue and stress analysis under 15 μm input displacement

**Notes:**
(a) Life cycles simulation with minimum life cycles 1.6649e13; (b) stress analysis at the maximum stress of 111.28 MPa
3. The principle of modular stage design

The basic idea underlying modular design is to organize a complex system, such as an electronic system, mechanical system and large program, as a set of distinct components that can be developed independently and then plugged together (Farritor et al., 1996). Although this seems to be a simple idea, the design principles are not only particularly relevant to parallel design but also can reduce the cost. In the micro/nanomanipulation field, stages are mainly manufactured monolithically without assembling. Some advantages of this kind of design are to improve the positioning precision and to reduce the assembling time. However, every coin has two sides, from the practical experience, different parts of the monolithic structure undertake various stress and deformation, it means that different components have different recycle life due to the repeated cyclic loading. To save the cost, the modular components can be replaced when they fail to work due to reaching fatigue life.

The conventional monolithic micromanipulation stage is fabricated using aluminum alloy material by employing EDM method, as depicted in Figure 3. This monolithic manipulation stage can be divided into four main components according to their different functions, in particular, amplifying mechanisms: to compensate the limited stroke of the piezoelectric actuator; flexure guider mechanism: to avoid/reduce the parasitic motion perpendicular to the driven direction; parallelogram flexure: to partially decouple the motion along x/y direction; and end-effector: to support the objects. During the literature review, some researchers divided the micromanipulation stage into more detailed components, i.e. beams and flexure hinges, such as primitive flexures because flexure hinges play a critical function in the micromanipulation stage (Yu et al., 2009). However, the assembling process is time costly and will produce more errors. In order to avoid these disadvantages, this study proposes a modular 2-DOF micromanipulation stage based on each component’s function.

The proposed modular 2-DOF micro-positioning stage is depicted in Figure 4, which consists of a bridge-type amplification module, flexure guider module, parallelogram flexure module and a mobile platform module and the dimension scale of this designed modular
stage is $157 \times 157$ mm. During the actuation process, the amplification mechanism will generate the parasitic motion, so a flexure guider module is needed to avoid/reduce this kind of motion. However, the stiffness of flexure guider module will cause the displacement loss, so flexure guider module should be made by soft material.

The right circular hinge is adopted as a revolute joint because of its better rotation accuracy compared with other types of flexure hinges. The P-810.10 piezoelectric actuator with the maximum pushing force of 50 N and travel range of 15 $\mu$m made by PI Inc., is chosen to drive the manipulation stage. To compensate the stroke of the piezoelectric actuator, the bridge-type amplification mechanism is adopted because of its fully symmetric structure which can reduce the thermal effect and parasitic motion. In this paper, the ABS material ($E = 1.1$ GPa, $\sigma = 25$ MPa, CTE = $7.8e^{-5}$ mm/°C) is adopted to fabricate the flexure guider mechanism, parallelogram flexure and end-effector; the aluminum alloy material T6-7075 ($E = 71.7$ GPa, $\sigma = 505$ MPa, CTE = $2.36e^{-5}$ mm/°C) is adopted to fabricate the bridge-type amplifier mechanism. The modular stage should work in constant room temperature because the adopted material has different coefficient of thermal expansion (CTE).

### 4. Manipulation stage analysis

In order to simplify the analysis process, the schematic diagram of the designed flexure-based parallel mechanism is shown in Figure 5. The reference frame $xoy$ is attached on the center of $GF$ with the distance of $2d$; $G$ and $F$ denote the end-point of each flexure guider mechanism, respectively; at the initial status the reference point $P$ is on the $y$ axis. The input force through the bridge-type amplifier and flexure guider mechanism drives the mobile platform. As depicted in Figure 5, the spring denotes the total stiffness of the bridge-type amplifier and flexure guider mechanism along the driven direction, through the simulation the value is derived as $K_{bsf} = 316.36$ N/mm. The pseudo rigid body (PRB) method is adopted to calculate the stiffness of right circular hinge. Each flexure hinge can be replaced by a revolute joint and torsional spring and $K$ denotes the rotational stiffness of the flexure hinge. Parameters of the designed compliant parallel manipulation are shown in Table I.
And $K$ can be calculated by the following equation (Meng et al., 2013):

$$K = \frac{2Ewl^2S}{9\pi r^{4.5}} \quad (1)$$

Here $E$ represents the Young’s modulus of the material, and other parameters of the flexure hinge are presented in Table I.

### Modular precision positioning stage

**4.1 Bridge-type mechanism analysis**

Bridge-type amplification mechanisms are usually adopted to amplify the stroke of piezoelectric actuators because fully symmetric structure can reduce thermal effect and parasitic motion. As shown in Figure 6, which is one quarter of the bridge-type amplifier, when the input voltage is applied, the piezoelectric actuators produce an input stroke and propel the external load to move along the perpendicular direction. As shown in Figure 6(a), when the input stroke $X$ is applied, the bridge-type amplifier will generate the output displacement $Y$ due to the rotational angle $\alpha$ of the link arm. Figure 6(b) depicts the kinematic model of quarter bridge-type amplifier. Here, $\beta$ denotes initial incline angle of the link arm and $L$ denotes the total length of the link arm and flexure hinges. Therefore,
the input displacement and output displacement can be written as a function of geometric relations (Figure 7):

\[ X = L(\cos(\beta - \alpha) - \cos \beta) \]  
\[ Y = L(\sin \beta - \sin(\beta - \alpha)) \]  

So the amplification ratio of the bridge-type amplifier can be derived as follows:

\[ R_{\text{amp}} = \frac{Y}{X} = \frac{\sin \beta - \sin(\beta - \alpha)}{\cos(\beta - \alpha) - \cos \beta} = \cot \beta \]  

here we assume that the rotational angle \( \alpha \to 0 \).

Based on the architectural parameters of the designed mechanism, the value of \( \beta \) is 14.57° and the theoretical amplification ratio is equal to 3.8473. To validate the theoretical analysis, the simulation has been conducted via Workbench software. The maximum output displacement of the flexure guider is 56.297 \( \mu \)m when the piezoelectric actuator achieves full input. Referring to the Figure 8 in which the amplification ratio is 3.753, the error is about 2.4 percent.
4.2 Kinematic analysis

As shown in Figure 7, the mobile platform is connected with two identical parallelograms, the points $e$ and $f$ denote the center point of AB and CD, respectively. The vectors $ef$ and $fp$ with the fixed length $b$ and $c$ have the same direction. Let $r = [r_1, r_2]^T$ be the input vector applied on the parallelogram joint variables, where $r_i = R_{amp} q_i (i = 1, 2)$ denote the output strokes of the piezoelectric actuators. The position of the mobile platform in the reference frame $xoy$ is denoted by the vector $p = [x, y]^T$.

4.2.1 Inverse kinematic analysis. The inverse kinematics is to solve the exact values of the actuators given the position of the mobile platform. Referring to the yellow line, as shown in Figure 7, a vector-loop equation can be written as follows:

$$\overrightarrow{P} = d\overrightarrow{d_i} + r\overrightarrow{a_i} + b\overrightarrow{b_i} + c\overrightarrow{c_i}$$

where $\overrightarrow{d_i}$ is the unit vector of $oG$; $\overrightarrow{a_i}$ is the unit vector of $Ge$; $\overrightarrow{b_i}$ is the unit vector of $ef$; and $\overrightarrow{c_i}$ is the unit vector of $fp$. Here, $\overrightarrow{a_i} = \overrightarrow{c_i} = (-\hat{c}\gamma, \hat{s}\gamma)$, where $\hat{c}$ stands for cos, $\hat{s}$ stands for sin.

Here, we define $\overrightarrow{m_i} = \overrightarrow{p} - d\overrightarrow{d_i} - c\overrightarrow{a_i}$, so the following equation can be derived:

$$\overrightarrow{m_i} = r\overrightarrow{a_i} = b\overrightarrow{b_i}$$

So, $q_i$ can be solved with the help of the above equation. Due to the configuration of this parallel mechanism, only negative square roots are chosen for actuated values and they can be written as follows:

$$q_i = \frac{1}{R_{amp}}(x + d)\hat{c}\gamma + y\hat{s}\gamma - c - \sqrt{b^2 - [(x + d)\hat{s}\gamma - y\hat{c}\gamma]^2}$$
Thus, the output stroke of the piezoelectric actuators can be solved using Equations (7) and (8).

4.2.2 Forward kinematic analysis. The forward kinematics is to solve the position of the mobile platform given a set of input values of the actuators. To solve the mobile platform position \( x \) and \( y \), we define \( \vec{n}_i = \vec{d}_i + (r + c) \vec{a}_i \). Based on Equation (5), the following equation can be derived:

\[
\vec{p} - \vec{n}_i = b \vec{b}_i
\]

The following equation can be obtained by dot-multiplying Equation (9) with itself:

\[
x^2 + y^2 - 2n_i x - 2n_i y + 2n_i^2 = b^2
\]

Also, Equation (10) can be expanded as the following two equations:

\[
[x + d - (r_1 + c) \vec{c}_1]^2 + [y - (r_1 + c) \vec{s}_1]^2 = b^2
\]

\[
[x - d + (r_2 + c) \vec{c}_2]^2 + [y - (r_2 + c) \vec{s}_2]^2 = b^2
\]

where \( r_i = R_{\text{amp}} f_{rb} \) referring to Equations (11) and (12), it means that the solutions of the forward kinematics are located at the intersection of the two circles which have radius \( b \) and the center of the two circles are \((-d + (r_1 + c) \vec{c}_1, (r_1 + c) \vec{s}_1)\) and \((-d + (r_2 + c) \vec{c}_2, (r_2 + c) \vec{s}_2)\), respectively.

4.3 Static analysis

The relationship between applying force and displacement of the mobile platform can be derived through the static analysis. The PRB method can simplify the analytical process of flexure-based mechanism. As shown in Figure 7, the black line denotes the initial position of the micromanipulation stage and red line denotes the position after applying the actuation force. With applying the driven force \( F_i (i = 1, 2) \), the parallelogram will have a rotational angle \( \delta_i (i = 1, 2) \) and mobile platform will have a displacement \( d_i (i = 1, 2) \) along the actuation direction. The force-deflection relationship can be derived as follows:

\[
F_1 = \frac{4K(\delta_2)}{(r_2 + bc\delta_2 + c)} + K_{b + f}r_1 \quad F_2 = \frac{4K(\delta_1)}{(r_1 + bc\delta_1 + c)} + K_{b + f}r_2
\]

where \( \delta_i (i = 1, 2) \) denotes the rotational angle of the parallelogram ABCD and \( K \) is the stiffness of the flexure hinge.

The dynamic performance of the stage is decided by the natural frequency of mechanism, which has an influence on the sensitiveness to the environmental vibrations. However, these characteristics are mainly derived from experiment, which will be conducted in our future work.

4.4 Workspace analysis

The workspace of the micromanipulation stage can be defined as the space that can be reached by the reference point \( P \) attached on the mobile platform. Parallel mechanisms have relatively
small workspace, compared with serial mechanism. One of the purposes of the proposed modular stage is to get a large workspace with piezoelectric actuators. Thus, the workspace is an important index to evaluate the performance of the micropositioning stage.

4.4.1 Constraint condition 1: limited input stroke. As mentioned above, the adopted piezoelectric electric actuator has limited stroke. Here, the maximum displacement of the adopted actuator is \( Q \), so the following inequation can be derived:

\[
0 \leq q_i \leq Q
\]  

(14)

where \( i = 1, 2 \). As aforementioned, Equations (11) and (12) represent the two circles and the intersection area of the circles subjected to the piezoelectric actuator motion range limits can be derived. Thus, workspace \( W_{(x,y)} \) subjected to the stroke of piezoelectric actuator can be derived by following equations:

\[
W_{(x,y)} = S_{(11)} \cap S_{(12)}
\]  

(15)

4.4.2 Constraint condition 2: limited rotation scope of flexure hinge. The maximum rotational scope of the flexure hinge depends on the elastic modulus of the material. Let \( \delta^m_i \) (\( i = 1, 2 \)) be the maximum rotational angle of the link BC relative to its initial position angle \( \delta^0_i \). When the maximum angle \( \delta^m_i \) increases, the maximum stress \( \sigma_{\text{max}} \) occurs at the outermost point of the flexure hinge with minimum thickness \( t \). Let the yield strength be \( \sigma_y \), thus

\[
\sigma_{\text{max}} = \frac{K_i \delta^m_i (t/2)}{I} = \frac{6K_i \delta^m_i}{wt^3} = \sigma_y
\]  

(16)

where \( I = \frac{wt^3}{12} \) and \( K_i \) is the stiffness of the parallelogram.

The workspace of the positioning stage subjected to the rotational scope of the flexure hinges can be written as \( |\delta_i| \leq \delta^m_i \), so \( -\delta^m_i \leq \delta_i - \delta^0_i \leq \delta^m_i \). Then, the following inequation can be derived:

\[
\tan (\delta^0_i - \delta^m_i) \leq \tan (\delta_i) \leq \tan (\delta^0_i + \delta^m_i)
\]  

(17)

So the constraint inequation can be expressed as follows:

\[
\tan (\delta^0_1 - \delta^m_1) \leq \frac{y - (r_1 + c)\delta^0_1}{x + d - (r_1 + c)\delta^0_1} \leq \tan (\delta^0_1 + \delta^m_1)
\]  

(18)

\[
\tan (\delta^0_2 - \delta^m_2) \leq \frac{y - (r_2 + c)\delta^0_2}{x - d + (r_2 + c)\delta^0_2} \leq \tan (\delta^0_2 + \delta^m_2)
\]  

(19)

Thus, the workspace of the manipulation stage can be calculated with the help of Equations (11), (12), (18) and (19).

Based on the aforementioned kinematic analysis, constraint conditions and architecture parameters of the mechanism, the workspace of the mechanism can be derived. As shown in Figure 9, the area \( S_{1234} \) denotes the workspace subjected to the limited stroke of the piezoelectric actuators and the area \( S_{1'2'3'4'} \) denotes the workspace subjected to the rotational limits of the flexure hinges. Obviously, the workspace of the stage is the intersection of these two areas \( (S_{1234} \cap S_{1'2'3'4'}) \). Referring to the Figure 8, the reachable workspace area of this mechanism is \( S_{1234} \), which is mainly determined by the output stroke of the piezoelectric actuators.
4.5 Coupling motion analysis

In this paper, a 2-DOF modular positioning stage fabricated with two different materials, namely, aluminum alloy and ABS, is proposed. In this case, the amplification mechanism is made by 7075-T6 and the rest components are made by ABS material. The output displacement simulation results of end-effector are depicted in Figure 10, which are under the condition of maximal input displacement 15μm. Referring to Figure 10(a), the end-effector will generate two types of motion, i.e. Δx and Δy, under the actuation. The FEM analysis results of the micro-positioning stages which are fabricated by the aluminum alloy (A.A) (7075-T6) and aluminum alloy-ABS (A.A-ABS) materials are shown in Table II, respectively.

Referring to Table II, the stage made by A.A-ABS material has relative large displacement under the equal constraint and input displacement conditions compared with that of A.A monolithic structure stages. It is because stiffness along the driven direction of the A.A monolithic structure is larger than that of the modular structure and it causes displacement loss. Meanwhile the modular structure can decrease coupling ratio dramatically compared with the monolithic structure with the same architectural parameters. In order to reduce the coupling ratio, many kinds of total symmetric structures have been designed. However, these structures improve the stiffness along the driven direction, and cause displacement loss. The stress simulations are also performed in Figure 11 under different loading conditions which can provide us maximum stress location information and guide us to replace the module in advance.

5. Conclusion

A 2-DOF modular compliant parallel mechanism utilizing two different materials is proposed in this paper. Based on the function of each component, the monolithic positioning stage is divided into following four parts: amplification mechanism, flexure guider mechanism, parallelogram flexure and end-effector. So the manipulation stage can be assembled by these modules for different purposes. Meanwhile, the proposed stage is analyzed by the developed PRB model, the kinematics and force-deflection relationships are derived. Taking the stroke of the piezoelectric and rotational scope constraints into consideration, the computational workspace of this modular manipulation stage is about 93×93μm which can satisfy the design goals. In addition, the FEA is conducted by Workbench software to compare the characteristics of the monolithic structure with modular structure and validated that the modular structure has less coupling motion.
Notes: (a) Schematic about end-effector motion; (b) aluminum alloy monolithic structure with y direction input; (c) aluminum alloy monolithic structure with x and y direction input; (d) ABS-aluminum alloy modular structure with y direction input; (e) ABS-aluminum alloy modular structure with x and y direction input.
The dynamic characteristics analysis, error analysis and positioning accuracy of the modular stage will be conducted in our future work. Moreover, developing some modules which can be used to assemble a planar and spatial stage for different purposes is our another goal.

References


**Corresponding author**
Yangmin Li can be contacted at: yangmin_li@hotmail.com

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: permissions@emeraldinsight.com