Kinematics Characterization of an Origami-Inspired Parallel Manipulator for pCLE

Xu Chen*, Michail E. Kiziroglou and Eric M. Yeatman

***Abstract*— The paper presents a origami-inspired miniature delta robot for probe-based confocal laser endomicroscopy (pCLE) manipulation. A pCLE is a soft and deformable miniaturized endoscopy based on optical fibres. Piezoelectric benders are used for actuation. The volume of them are $28\ mm \times 25\ mm \times 23\ mm$. The parallel robot is 3D-printed and origami-procedure-deformed. Blade flexures serve as compliant joints of it. Kinematics characterization was conducted by performing open-loop control motion experiments. The results reveal that the origami-inspired miniature parallel robots has good accuracy and precision. Further design optimisation could offset the effects of hysteresis, gravity and geometry deviations caused by fabrication. A smaller-size delta robots with visual feedback is the next step work as well.**

I. INTRODUCTION

A probe-based confocal laser endomicroscopy (pCLE) has been widely used in microsurgery [1]. Endomicroscopy tools have a small diameter and low stiffness. They capture high quality images of single-layer cells, which allows the identification of tissue condition during surgery. However, a pCLE's fibre body is soft, and its view area is very small. Therefore, a pCLE requires a precise dynamic optical zoom and focus control in order to provide high-resolution confocal scanning in close proximity to the tissue surface [2]. A miniature manipulation system with precise micro-motion control for this application is highly desirable for extending the range as well as the cell morphology characterisation capability of pCLE systems.

A miniature manipulator intended for pCLE ought to carry out high accuracy and precision motion, high degree of freedom, high-power-density and a large workspace [3]. Some research on developing such systems has been reported in the literature [2], [4]. In addition, existing microscale manipulator designs, originally intended for other application may also be considered. For example, Lyu et al. presented a piezoelectric-actuated biaxial microgripper in [5], comprising a long strike parallel mechanism for stiff object manipulation. Power et al invented a force-sensitive microscale 3D-printed gripper on the tip of optical fibre for drug delivery and microbiopsy [6].

Referred to existing manipulation technologies, parallel manipulators, who have close-loop kinematics chains, possess more stability, a larger load-to-weight ratio, higher natural frequencies and higher accuracy over traditional serial ones [7]. Origami-inspired compliant parallel manipulators has the advantage of avoiding assembly and backlash on joints that affect the precision of the manipulator [8], [9]. Piezoelectric benders can provide faster response, more accurate motion and higher output force to weight ratio. Combining piezoelectric benders with compliant structures can not only amplify motion and transfer motion to different types [10], but also involve spring element to overcome creeping phenomenon of piezoelectric materials [11].

This paper introduces a 3-DoFs origami-inspired delta robot. They represent a primary stages of the study on micro-actuators for medical robotics. The actuation mechanism of it are three piezoelectric benders. Section II indicates the design and fabrication of the it. Section III presents the kinematic analysis of the prototypes of the delta robot. Kinematics characterization experiments and results of the robot are in Section IV. Section V draws a conclusion and foresees the potential improvement and future applications.

II. DESIGN AND FABRICATION

The parallel robot generally consists of three parts, a compliant actuation mechanism, three piezoelectric benders, and a support frame. Compliant actuation mechanisms are transferred from a traditional delta robot by replacing all joints into blade flexures [12]. The structure was 3D-printed in a flat form for fabricating thin blade flexures, and subsequently deformed to be a 3D structure through an origami-like procedure. The advantage of this method is that the structure can be rapidly fabricated as a single solid by a single 3D printing fabrication. In this way, very thin blade hinges are achievable in small scale. In addition,it allows the implementation of the spring stiffness required for optimal exploitation of the small displacement provided by piezoelectric actuating elements. The 3-DoFs manipulator involves three additional parallelogram system at each arm.

A. Flat Structure Design

In Fig.1 (a)(1), which are the top view of the flat structures, the mobile platform was designed at the geometry centre of the whole structure. It is a hexagon-like shape with three longer edges, and its three longer edges are centrosymmetric to each other. The flat structure of the delta robot have four-bar parallelogram systems. (Fig.1 (a)(2)).

B. Fabrication

A Connex3 Objet500 PolyJet 3D Printer is used for the fabrication of the flat strucure. Objet500 printer offers not only rigid and soft material but also digital materials for

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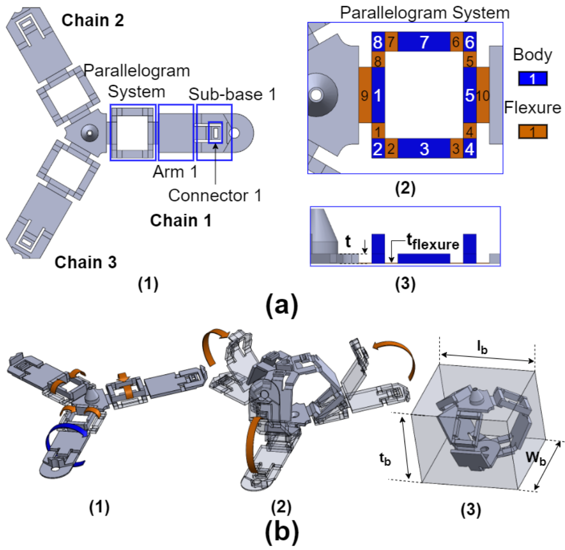

Fig. 1. Overview of the compliant delta structure. (a): (1) Top view of the flat structure. (2) Top view of Parallelogram System. (3) Partial Side view of the flat structure. (b): Schematic of the first stage (1) and second stage (2) of origami procedures, as well as the completed compliant structure (3).

TABLE I
SPECIFICATION OF THE TYPE 6 PIEZOCERAMIC BENDING ELEMENT [15]

Parameters	**Type 7**	**Parameters**	**Type 7**
Total length [mm]	32.5	Total displacement [mm]	1.4
Free length [mm]	27.5	Blocking force [mN]	150
Width [mm]	1.9	Capacity per ceramic side [nF]	13.5
Thickness [mm]	0.7	Operating voltage [V]	230

realising monolithic stiffness gradients [13]. In this work, VeroWhite™ material was used to fabricate the flat structure.

C. Origami Procedures

Origami procedures are divided into two stages. The first is illustrated in Fig.1 (b)(1), which builds up parallelogram systems. The combinations of flexure joints in 3D parallelogram systems serve the function of spherical joints of delta robots [14]. After that the structure is flipped 180 degrees around the blue arrow. The second stage is to build up the base of the mechanism. The completed structure is in Fig.1 (b)(3). The initial posture of the structure relies on the position of piezoelectric benders. The volume of the compliant structure is $L_b \times W_b \times t_b = 28\ mm \times 25\ mm \times 23\ mm$, as Fig.1 (b)(3).

D. Piezoelectric Bender

Piezoelectric benders used are Type 6 piezoceramic bending element from Johnson Matthey Piezo Products GmbH, which is a parallel-polarization bimorph. Table.I [15] is its specifications table. Three benders are inserted into three Connectors and vertically assembled with respect to the base. During actuation, they change the angle of each arm, leading to controllable motion of the mobile platform.

TABLE II
SPECIFICATION OF CAD MODEL AND MATERIAL PROPERTIES

CAD Parameters (mm)					
L	10	l	10	t	1
R	8	r	4.5	$t_{flexure}$	0.06
Material Properties					
Density (kg/m^3)		1170	Modulus of Elasticity (MPa)		2870
Flexural Strength (MPa)		76	Flexural Modulus (MPa)		1718

III. PROTOTYPE FORWARD KINEMATICS

The prototype of the compliant delta robots is link-and-joint delta robot with three identical kinematic chains. Each chain contains one revolute joint (R), one arm (L), one pair of forearms (l), and two pairs of spherical joints (S), as shown in Fig.2 (a) (b). The four spherical joints (S) connect forearms to corresponding arms and the mobile platform, respectively. A kinematic analysis of the 3-DoFs robot is performed. A force and stiffness charaterization is not included in this work. Experimental results of the linear force capability of a similar implementation are in [16].

Forward kinematics of the prototype is to find out the position of the mobile platform from the $\theta_{1,2,3}$, which are the angles of each corresponding revolute joint. The angles are also the actuation input of the parallel robot. The angle-position relationship between could be analysed based on Fig.2 (a). In Fig.2(b), kinematic chain 1 is considered separately and analysed with respect to coordinate 1. The base is fixed. The point B is the center of the base, which is also regarded as the origin of the ground Cartesian coordinate system 1, 2 and 3. R_i represents the revolute joints. According to [17], the mobile platform is always parallel to the base. The simplified model is in Fig.2 (c). The kinematic equation for calculating the position of C will be:

$$l - \left\| rotz(\phi_i) \begin{bmatrix} 0 \\ (B-r) + L \times cos(\theta_i) \\ L \times sin(\theta_i) \end{bmatrix} - \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix}) \right\| = 0 \quad (1)$$

where:

$$\begin{cases} \phi_i = \frac{-2pi}{3} * (i-1),\ i = 1,2,3 \\ rotz(\theta) = \begin{bmatrix} cos(\theta) & -sin(\theta) & 0 \\ sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{cases} \quad (2)$$

From known input angles θ_1, θ_2 and θ_3, the position C in the global coordinate can be derived from (1) and (2).

A. Displacement vs Input Voltage

There were two steps to explore the relationship between displacement of the mobile platform and input voltage on the three piezoelectric benders. The first step was finding out the relationship of displacement of the platform and those at the contacting points of the three benders. In the analytical model, the platform displacement is proportional to a linear combination of the contact displacements. This is because the delta robot is a reversible closed kinematic chain [17].

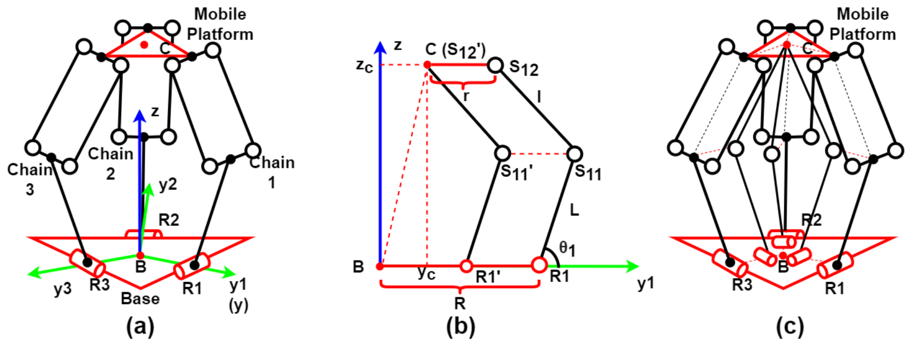

Fig. 2. Schematic diagram for forward kinematics analysis. (a) The prototype delta robot and local coordinate layout. (b) Chain 1 in coordinate 1 (x axis toward vertival and out of the page). (c) Simplified model.

- To drive the mobile platform translation in Z direction, the contact points 1,2,3 should follow the same motion, while $Input1 : Input2 : Input3 = 1 : 1 : 1$.
- X direction, $Input1 : Input2 : Input3 = 0 : 1 : -1$.
- Y direction, $Input1 : Input2 : Input3 = -2 : 1 : 1$.
- The stiffness of each degree of freedom of the structure is constant and independent to its posture.

On the basis of the first step, the second step was to find out the relationship between the displacement of the mobile platform and input voltage. The relationship of the voltage on piezoelectric benders and their deflection is also approximately linear [18].

IV. Open-Loop Control Experiment

A. Experimental Set-up

An open-loop control experiment was designed for the validation of the delta robot. Three kinds of 2D shapes were performed by the mobile platform in the experiment: circle, star, spiral, and raster. According to Fig.3 (a) (1), the experiment set-up consists of a optical camera (VHX-6000 digital microscope, Keyence), a signal generator (CompacRIO cRIO-9025, National Instruments, US), three voltage amplifiers, a vertical stage, an optical table and copper tape connectors. The voltage amplifiers used are two E-413 DuraAct and PICA Shear Piezo Drivers (±250V) and one WMA-300 high voltage amplifier of Falco System (±150V). The maximum input voltage magnitude was 150 V. Then, employing the calculation results and control algorithm through LabVIEW. Fig.3 (b) illustrates the results of the two experiment.

B. Results and Discussion

Fig.3 (b) are the result diagrams. The results generally have same shape but are 30% smaller compared to the desired paths. As for Fig.3 (b) (1), it shows a 10-time-cycled circle motion. The plenary deviation of the geometry centre of the 10 circles is within 0.05 mm. After 10 times cycle, the geometry centre of the last circle shift around 0.04 mm compared with the first one whose centre is mostly closed to the desired centre of the trajectories. Over 80% centre deviation relied on the shifting. The spiral shape in Fig.3 (b) (2) also reveals this phenomenon. It possibly results from the hysteresis of the piezoelectric material. Fig.3 (b) (3) and (4) are the results of raster and star shape motion, respectively. These two experiments were designed to test the translation ability of the robot. The vertical translation performance is relatively stable. In Fig.3 (b) (4), a star shape motion is presented, exhibiting overall good control, with deviations in horizontal motion and shifting, similar to the previous cases.

The experiment results of four kinds of shape motion validate the compliant robot's ability to achieve desired motion by controlling input voltage signals on the piezoelectric benders. It also validates the control strategy in Section III A.

V. Conclusion

The paper introduces a new approach for the fabrication of a miniature compliant delta robot. The employment of a 3D printed structure combined with origami processing not only simplifies the craftsmanship of the compliant structure but also increases the accuracy and precision due to the use of a single homogeneous material. The approach also extends the fabrication of compliant structure with different materials, such as metals, and different methods, such as laser cutting. Piezoelectric benders are ideal actuation mechanisms for miniature compliant structures. They could achieve considerable motion and force while occupying a small space. Limitations of the proposed method include effects of flexure hysteresis and gravity, as well as high strain energy storage in flexure joints, which reduces output force. Hysteresis and gravity deviation can be addressed by suitable voltage control circuit design.

For future work, there are two potential extensions on the compliant delta robot based on the existing facility. The first is to achieve micro-size compliant parallel robot for micro-manipulation. The second is a 6 DoFs parallel robot by applying more kinematic chains and piezoelectric benders.

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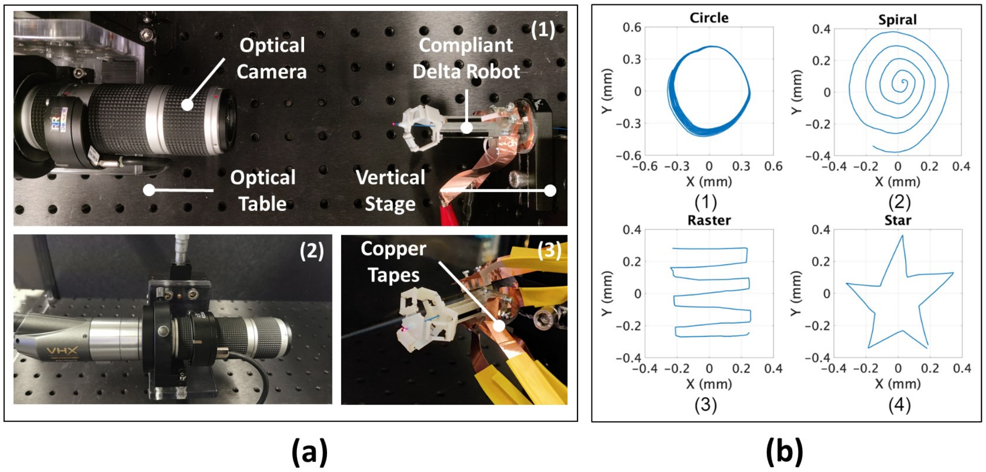

Fig. 3. (a): (1) Overview of experimental set-up. (2) Optical camera for motion capture. (3) The compliant delta robot with copper tapes connected. (b): Result diagrams for four motions. (1) Ten-time-cycled circle. (2) Five-time-cycled spiral. (3) Raster. (4) Star.

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