Design and kinematics of a 3-DOF compliant triglide micromanipulator

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Abstract. This paper proposes a novel 3-degrees of freedom (DOF) compliant parallel micromanipulator. The design of the mechanism is based on triglide parallel manipulator. The compliant version of the triglide is prepared by making use of flexure joints. Displacement amplifiers are incorporated in the design to increase range of motions. The pseudo-rigid-body modeling technique is then used to formulate and solve the inverse kinematic problem for the design. To check the correctness and accuracy of the analytical kinematic model FEA simulations are performed in Abaqus-6.14 environment. Simulation results reveal that the proposed micromanipulator can perform different motions very effectively. Additionally, it is found that results predicted by the analytical model conform very closely to the simulation outcomes. The errors are very low, and the motions involve negligible parasitic motions.

1. Introduction

A micromanipulator is a device that usually operates under a microscopic field with the objective of manipulation of tools precisely [1]. Based on application they are also referred to as a micro-positioning stage. Micromanipulators find applications in a variety of fields. Biological cell manipulation, optical alignment, micro-surgery, micromachining, scanning electron microscopy, and micro-assembly are some of the applications.

A mechanism that gets its mobility from the deformation of some of its members is called a compliant mechanism [2]. Due to some of their inherent characteristics, compliant mechanisms are one of the most popular solutions for micromanipulation. Compliant mechanisms with the parallel structure are called compliant parallel micromanipulators or CPMs.

Most of the micromanipulation activities require 3-DOF; hence the demand for 3-DOF CPMs is highest among all. In their paper Koseki et al. [3] presented a translational 3-DOF micromanipulator. The authors used matrix method for kinematic modeling of the mechanism. Stiffness modeling of a 3-DOF flexure parallel mechanism was discussed by Pham and Chen [4]. A novel design of a 3-DOF translational CPM was proposed by Li and Wu [5]. The authors used pseudo-rigid-body modeling for the analysis of the mechanism. For surface grinding, Zhang et al. developed a 3-DOF micro-positioning stage. The design has a high stiffness to give better performance at high frequencies. Some other works in the relevant area can be found in [6], [7], and [8]. Piezo-actuators are generally considered as the ideal choice for the actuation of CPMs. However, they suffer from the drawback of low range. In this paper, a novel design of CPM
is proposed. To increase the range of motions, the proposed design incorporates displacement amplifiers. In one of their earlier works [9], the authors successfully employed a similar amplifier to increase the range of motion of their 6-DOF compliant Stewart micromanipulator. In each of the three displacement amplifiers, there are two similar parallelograms mirroring each other. This arrangement gives the mechanism more stiffness, and hence better dynamic performance. The double parallelogram structure also eliminates unwanted parasitic input motions.

The organization of the rest of the paper is as follows. Section 2 presents the design of the proposed micromanipulator. Kinematic modeling of the mechanism is formulated in Section 3. In Section 4, the results of the kinematic analysis are summarized. The FEA validation of the results is also discussed in this section. Finally, concluding remarks are outlined in Section 5.

2. Design of compliant triglide micromanipulator
The design of the micromanipulator is based on the 3-DOF triglide parallel manipulator. A triglide is a spatial parallel manipulator and is capable of producing 3-DOF xyz motions. For the preparation of the compliant version of the triglide, flexure joints are used. The current design involves use of revolute and spherical flexure joints (see Fig. 1). Figure 2 shows the final compliant version of the triglide. In the design, three displacement amplifiers are introduced to improve the range of motion of the mechanism. The displacement amplifier consists of two mirroring parallelograms made with revolute flexures. Each parallelogram receives input from an actuator, and then works as a lever to amplify the input. The output of the displacement amplifier connects to the platform by a passive parallelogram made by four spherical joints and two cylindrical links as represented in Fig. 2.
3. Kinematics

Pseudo-rigid-body (PRB) modeling is a technique in which the flexible members or flexure joints of a compliant mechanism are replaced by suitable conventional kinematic joints. The resulting mechanism can then be analyzed through already available methods of robot kinematics or theory of mechanisms.

3.1. Inverse kinematics

The inverse kinematics problem for a mechanism concerns with finding the inputs for a desired position of the end effector. For the present case, the inverse kinematics can be solved by considering the loop-closure equation for any of the three limbs. With reference to Fig. 3, the loop-closure equation can be written as

\[
\begin{bmatrix}
 x \\
 y \\
 z 
\end{bmatrix} + \begin{bmatrix}
 r \cos(\alpha_i) \\
 r \sin(\alpha_i) \\
 0 
\end{bmatrix} + \begin{bmatrix}
 d_x \\
 d_y \\
 d_z 
\end{bmatrix} = \begin{bmatrix}
 R \cos(\alpha_i) \\
 R \sin(\alpha_i) \\
 0 
\end{bmatrix} + \begin{bmatrix}
 0 \\
 0 \\
 h 
\end{bmatrix} + \begin{bmatrix}
 -S_i \cos(\alpha_i) \\
 -S_i \sin(\alpha_i) \\
 0 
\end{bmatrix} 
\]

(1)

This finally yields the following quadratic equation in \( S_i \).

\[
S_i^2 + 2(x \cos(\alpha_i) + y \sin(\alpha_i) - K)S_i + x^2 + y^2 + (z-h)^2 + K^2 - d^2 - 2K(x \cos(\alpha_i) + y \sin(\alpha_i)) = 0 
\]

(5)

where, \( R - r = K \) and \( d_x^2 + d_y^2 + d_z^2 = d^2 \). Out of the two results yielded by the Equation 5, one corresponds to the case wherein the actuations would be in the order of the size of the mechanism. Due to limits in joint motions, this magnitude of actuation is not permitted in the flexure-based micromanipulators. The other feasible solution of this equation is presented below.

\[
S_i = K - x \cos(\alpha_i) - y \sin(\alpha_i) - \sqrt{d^2 - h^2 - x^2 \sin^2(\alpha_i) - y^2 \cos^2(\alpha_i) - z^2 + xy \sin(2\alpha_i) + 2zh} 
\]

(6)

This equation provides the actuations needed for any position reached by the end effector.
Table 1: Values of major structural parameters of the design (in mm).

| b  | d  | h  | l₁ | l₂ | l₃ | r  | R  | r₀ | r₁ | r₂ | t₀ | t₁ | t₂ |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 30 | 351| 270| 25 | 125| 80 | 113| 337| 5  | 8  | 1  | 2  |    |    |

4. Results and FEA validation

The analytical model for inverse kinematics was formulated in the previous section. In this section, the results from the analytical model are obtained, and then they are validated with the help of FEA simulations. With reference to Fig. 1 and Fig. 2, the values of the major structural parameters of the micromanipulator are presented in Table 1.

4.1. Results from analytical inverse kinematics model

From Eq. 6, one can obtain the actuation values for a desired position of the end effector or platform. Table 2 presents a compilation of actuations needed for four different types of movements of the platform.

Table 2: Inverse kinematics results obtained from analytical model.

| Output motion | Required actuation (in µm) |
|---------------|----------------------------|
| (in µm)       | S₁  | S₂  | S₃  |
| 40, 0, 0      | -4.000 | 8.000 | -4.000 |
| 0, 40, 0      | -6.928 | 0.001 | 6.928 |
| 0, 0, 40      | -9.598 | -9.598 | -9.598 |
| 19, 19, 19    | -9.751 | -0.759 | -3.168 |

4.2. Validation of the results using FEA simulations

In this section, the actuations obtained from the analytical model will be given to the FEA model of the micromanipulator. Furthermore, it will be checked whether the mechanism performs the expected motions accurately or not. The FEA model of the compliant triglide is prepared in the Abaqus-6.14 environment. For meshing C3D10 element is used. Moreover, as the deformations are expected to be concentrated mainly at flexure joint areas, they are provided with a fine mesh. Table 3 summarizes a comparison between the expected analytical motions and actual motions performed by the FEA model. Deformations contours for the FEA results are shown in Fig. 4. The results presented in Table 3 can be interpreted as follows. The maximum error in the exploration was found to be less than 7%. This error can be attributed to the out of axis deformation of the flexures, and deformation of the connecting links which were assumed to rigid in the kinematic model. On the other hand, the undesired parasitic motions for the mechanism were found to be below 0.18%. This shows that the output of the proposed design involves negligible parasitic motion.
5. Conclusions

A novel design of a compliant 3-DOF micromanipulator was presented in this paper. The compliant version of the triglide parallel manipulator was successfully prepared by making use of flexure joints. It was shown that the pseudo-rigid-body modeling could be very effectively employed to formulate the inverse kinematics model of the proposed design. The results indicated that the errors were within the acceptable limit, and the micromanipulator performed the desired motions with negligible parasitic motions.

The effect of payload and gravity was not considered in the present work. A stiffness model of the micromanipulator would give insights on the effect of payload on end-effector motion. Moreover, the proposed design in this paper is an initial version of the micromanipulator. To find the dimensions for optimal performance more elaborate analysis and testing are needed.

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