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A flexure-based five-bar mechanism for micro/nano manipulation

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ABSTRACT

This paper presents the design, fabrication and experimental testing methodologies of a flexure-based five-bar mechanism. Such mechanisms will be indispensable in micro/nano scale operations. To overcome the limited displacement of such flexure-based mechanisms driven by piezoelectric actuators, lever mechanisms are used to increase the working range in Cartesian space. The mechanical design of the flexure-based mechanism is first described and the kinematic model is established. The linearised relationship between the actuation space and the Cartesian space is developed according to the kinematic analysis. The finite element analysis (FEA) is carried out to examine the performance and validate the established kinematic model. The maximum stresses in the compliant mechanism and the amplification factors of the entire system are investigated to guarantee the long-term repeatability, accuracy, and functional requirements. A closed-loop control methodology is established to overcome the hysteresis of the piezoelectric actuators, and to improve the positioning accuracy of the entire system. Experimental investigation is carried out to cross validate the characteristics of the developed flexure-based mechanism.

1. Introduction

Micro/nano manipulation is one of the key enabling methodologies for the nanotechnology applications such as X-ray lithography, micro-manufacturing, bio-medicine, micro/nano surgery, and nano-metrology [1–4]. In these engineering and medical fields, the required motion and positioning precision is generally within the order of magnitude of a nanometer. It is well known that the positioning precision and resolution of manipulators, including micro/nano manipulation systems, mainly depend on their topology and mechanical structures, actuators and transducers, sensing and measurement techniques, and control methodologies [5–10]. Due to the backlash and stiction of the revolute joints and the geometric and dimensional errors of the components of the conventional manipulation systems, the conventional mechanisms cannot fulfill the requirements of the micro/nano manipulation tasks. Therefore, different mechanisms must be developed to overcome these problems. One of the best approaches to overcome the above problems is to utilize flexure-based mechanisms, where the conventional kinematic pairs are replaced by the flexure hinges. These types of joints have a number of advantages including no backlash, zero friction, and negligible hysteresis [11–14]. In addition, such flexure-based mechanisms can be monolithically manufactured and thus reducing assembly errors and guaranteeing the machining accuracy [15]. With the aid of fixture holding systems using 3-2-1 locating and constraining technique, the flexure-based mechanisms can be combined with the conventional macro-positioning manipulators to form dual positioning systems. Thus, a larger range of precision positioning can be achieved [16–19]. Recent research efforts have focused on the development of many aspects of the flexure-based mechanisms for conducting nano-scale tasks beyond the limits of human manipulation and patience [20–23]. The development of these design methodologies for flexure hinges, novel micro-actuators, and adaptive robust control strategies for precision positioning will enable the establishment of the micro-manipulators with high dynamic performance and resolution [24–29]. Further, it is becoming evident that the closed-loop piezo-driven parallel mechanisms made up of flexure hinges have a considerable potential for the applications in the micro/nano manipulation tasks [30,31]. Therefore, the design methodology is one of the important research areas in the applications of such parallel flexure-based mechanisms.

This paper presents the design, kinematic modeling and dynamic measurement methodologies of a flexure-based five-bar mechanism. The mechanical design and fabrication of the flexure-based mechanism is first described. Based on the configuration of the proposed mechanism, the kinematic model is developed. The linearised displacement mapping and relationship between

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the actuation space and the Cartesian space are developed according to the kinematic analysis. The finite element analysis (FEA) is carried out to examine the performance, and to validate the established kinematic model. The maximum stress encountered in the compliant mechanism is examined to guarantee the long-term repeatability and positioning accuracy. The closed-loop control methodology is utilized to overcome the hysteresis of the piezoelectric actuators and improve the positioning accuracy of the entire system. Experiments are conducted and results are analyzed to cross validate the characteristics of the developed flexure-based mechanism.

2. Mechanical design

The geometric model of the flexure-based five-bar mechanism with lever structure is shown in Fig. 1. The main components of the compliant mechanism include the rectangular links and flexure hinges. Compared with other types of flexure hinges, circular flexure hinge with rectangular cross-section has high precision for rotational accuracy and is the optimal choice as the revolute joint for precision mechanism design and construction. A stationary frame is used to support the compliant mechanism and connect with other equipment and manipulators.

The five-bar linkage, demonstrated by loop 1, is the main mechanism to implement 2-DOF (degree of freedom) planar motion. The location of the end-effector is one of the key factors to affect the kinematic and dynamic characteristics of the compliant mechanism. The end-effector is generally located at the mid-point of the central flexure hinge, and thus the entire mechanism has a symmetric kinematic and dynamic performance within the Cartesian space. However, it is not feasible for the end-effector to be located at the mid-point of a flexure hinge to implement micro/nano manipulation, and mount other tools and measurement sensors for closed-loop control. The main reason is that flexure hinge will generate elastic deformation during the motion of the five-bar mechanism, and the position and orientation of the mid-point of the flexure hinge are difficult to model and predict, and thus the positioning precision of the end-effector is seriously affected.

To overcome the above problem, the end-effector location is chosen at a point on one of the passive links as shown in Fig. 1. Due to no local elastic deformation, the position and orientation of the end-effector can be accurately predicted and controlled, the feedback measurement sensors can also be mounted onto the end-effector to form the closed-loop control and improve the static and dynamic performance of the five-bar mechanism. Furthermore, the kinematic performance of the end-effect within the Cartesian space can be improved by optimizing the structural parameters such as the link lengths and the initial angles of the five-bar mechanism. Thus, the end-effector of the five-bar mechanism can also achieve an approximately symmetric kinematic performance within the Cartesian space.

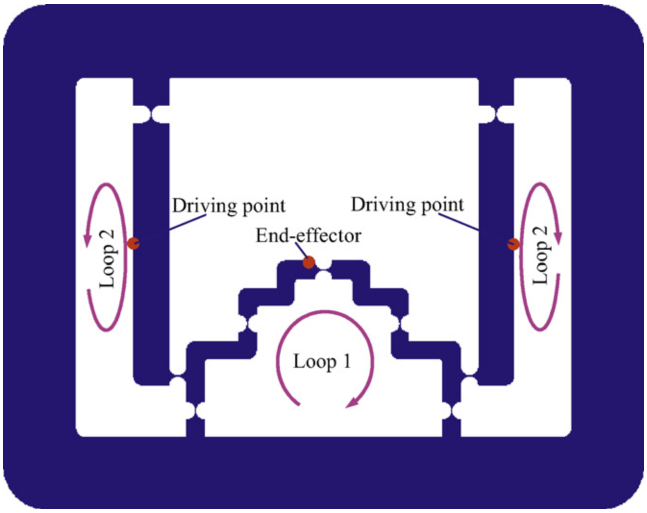

Fig. 1. Geometric model of the flexure-based five-bar mechanism.

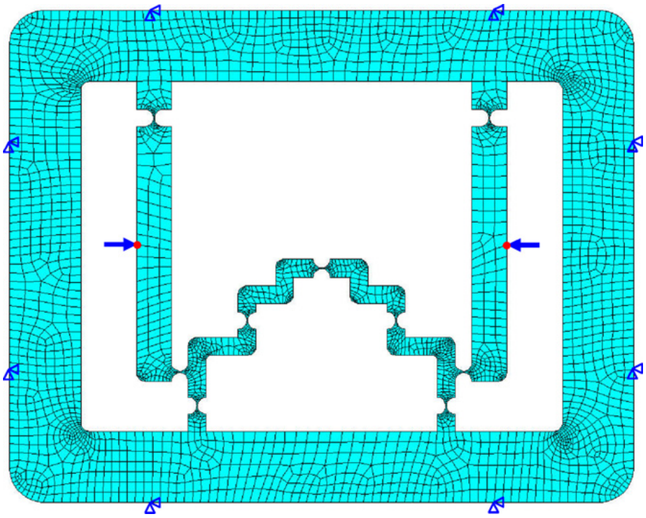

Fig. 2. Finite element model of the five-bar mechanism.

It is well known that the performance of the actuator significantly affects the static and dynamic characteristics of such compliant mechanisms. Piezoelectric actuators are generally utilized to drive flexure-based mechanism, due to their characteristics such as infinite resolution, zero backlash, no lubrication, and free of thermal generation. It must be emphasized that there exist nonlinearities such as hysteresis and creep when a piezoelectric actuator is under voltage control condition. Thus, it is necessary to develop closed-loop control methodologies to improve the positioning accuracy of the piezo-driven mechanisms. In addition, the limited output displacement is another disadvantage of such piezoelectric actuators. In order to obtain the required working range, a lever mechanism is proposed to increase the range of displacement of the piezo-actuated mechanism as shown in Fig. 1, where two lever mechanisms are introduced to drive the active links of the five-bar mechanism. The driving points for piezoelectric actuators are chosen at the middle of the lever. This indicates that the theoretical amplification factor is 2.

In order to guarantee the performance of the flexure-based five-bar mechanism described above, the finite element analysis (FEA) is carried out using the ANSYS software package. The displacement and the maximum stress profile of the flexure-based mechanism are investigated in the mechanical design. The finite element model (Fig. 2) is based on the physical model as shown in Fig. 1. A two-dimensional 8 node solid element, i.e. plane 82 is used to mesh the flexure-based mechanism. This type of element has quadratic displacement behaviour and is well-suited to model irregular shapes such as flexure hinges. Each node has two degrees of freedom comprising translations in the x and y directions, respectively. In order to improve the computational accuracy, the smart mesh method is utilized, and thus the element sizes are different for each part of the flexure-based mechanism and about quintile of the minimum dimension of the local region. The surfaces of the stationary frame are fixed and constrained in all degrees of freedom. The excitation source is the displacement applied by the piezoelectric actuators on the driving points of the flexure-based mechanism. The displacement of the end-effector, as well as the moving linkages and