Design & Implementation of

Large-Range Compliant Micropositioning Systems

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Preface

Micropositioning systems refer to positioning devices which are able to produce displacement down to sub-micrometer resolution and accuracy. Such devices are widely employed to realize a precise positioning of microrobotic end-effectors dedicated to precision manipulation and assembly applications. To cater for the precision requirement in relatively low-loading scenarios, flexure-based compliant mechanisms have been exploited extensively owing to their attractive merits in terms of no backlash, no friction, no wear, low cost, and vacuum compatibility. Unlike traditional mechanical joints, the repeatable output motion of a flexure mechanism is delivered via the elastic deformation of the material.

Typically, flexure mechanisms can deliver a translational displacement of less than 1 mm and a rotational displacement smaller than 1°. In modern precision engineering applications, there is a growing demand for micropositioning systems which are capable of providing large-range precision motion (e.g., over 10 mm translation and 10° rotation), yet possess a compact size at the same time. Such applications range from scanning probe microscopy to wafer alignment, lithography and fabrication, biological micromanipulation, etc. A precision positioning stage with a compact size allows the application inside a limited space. Additionally, a compact physical size enables cost reduction in terms of material and fabrication. For practical applications, once the kinematic scheme is determined, the structural parameters of the flexure mechanism need to be carefully designed to make sure that the material operates in the elastic domain without plastic deformation or fatigue failure.

Traditionally, the motion range is restricted by the mechanism design - due to the stress concentration and stress stiffening effects - and also constrained by the maximum allowable stress of the material. Intuitively, a larger motion range can be achieved by employing flexures with longer and more slender hinges. However, the length of the flexure hinge is usually constrained by the compactness requirement and the minimum width is restricted by the tolerance of the manufacturing process in practice. Hence, it is challenging to design a flexure micropositioning stage with a large stroke and compact size simultaneously. To this end, this book is concentrated on the design and development of flexure-based compact micropositioning systems with large motion ranges. Some innovative mechanism designs are presented for large-range translational and rotational positioning. Analytical modeling and finite-element analysis are carried out to evaluate the performance of the mechanisms. Prototypes have been developed for experimental investigations.

To implement a complete micropositioning system, suitable actuation and sensing schemes are selected. Once a micropositioning device is constructed by incorporating the flexure micropositioning stage, sensors, and actuators properly, its accuracy is dependent on a suitable control strategy. Usually, a micropositoining system is termed a nanopositioning system if it can provide the displacement resolution down to sub-nanometer or nanometer level. As typical control schemes, the proportional-integral-derivative (PID), sliding mode control (SMC), and model predictive control (MPC) algorithms are realized as examples to achieve a precise positioning of the micropositoining systems in this book.

The book also involves the design of large-range compliant grippers, which combine the large-range translational and rotational stages together. The realization of the gripper down to microelectromechanical systems (MEMS) scale is also demonstrated. Detailed examples of their analyses and implementations are provided. A comprehensive treatment of the subject matter is provided in a manner amenable to readers ranging from researchers to engineers, by providing detailed simulation and experimental verifications of the developed devices.

The book begins with an introduction to micropositioning techniques and provides a brief survey of development and applications in Chapter 1. According to the different implementations of micropositioning systems, the remaining ten chapters of the book are divided into four parts.

Part I consists of Chapters 2, 3, and 4, which address the design and implementation of large-range translational micropositioning systems. Specifically, Chapter 2 presents the design of a uniaxial translational positioning device by introducing the idea of multi-stage compound parallelogram flexure (MCPF). A voice coil motor (VCM) and a laser displacement sensor are adopted for the actuation and sensing of the developed stage, respectively. Control experiments are demonstrated to verify the stage performance. Chapters 3 and 4 devise large-range, parallel-kinematic, decoupled XY micropositioning systems, which can provide two-dimensional decoupled translations over 10 mm in each working axis. Several variations of the decoupled XY flexure stage are designed. While Chapter 3 proposes a monolithic structure design, Chapter 4 reports on a two-layer compact design of the parallel-kinematic XY flexure mechanism.

Part II is composed of Chapters 5, 6, and 7, which present multi-stroke translational micropositioning systems. Chapter 5 describes the design and implementation of a flexure-based dual-stage micropositioning system. A VCM and a fine piezoelectric stack actuator (PSA) are adopted to provide the long stroke and quick response, respectively. A decoupling design is proposed to minimize the interference behavior between the coarse and fine stages by taking into account the actuation schemes as well as guiding mechanism implementations. Chapters 6 and 7 propose the conceptual design of multi-stroke, multi-resolution uniaxial and two-dimensional micropositioning stages, respectively, which are driven by a single actuator for each working axis. The stages are devised based on a fully compliant variable-stiffness mechanism, which exhibits unequal stiffnesses in different strokes. Resistive strain sensors are employed to offer variable displacement resolutions in different strokes.

Part III includes Chapters 8 and 9, which deal with the design and implementation of large-range rotational micropositioning systems. Based on the idea of multi-stage compound radial flexure (MCRF), two kinds of rotary compliant stages are devised to achieve both a large rotational range over 10° and a compact size. Chapter 8 presents a rotational micropositioning device which is driven by a linear VCM and sensed by a laser displacement sensor, whereas Chapter 9 reports a rotational micropositioning system which is actuated by a rotary VCM and measured by a strain-gauge sensor. Analytical models are derived to facilitate the parametric designs, which are validated by conducting finite-element analysis (FEA) simulations. Experimental results reveal a large rotational output motion of the developed rotational devices with a low level of center shift.

As a typical application of the presented translational and rotational micropositioning stages, Part IV proposes the design and development of innovative large-range compliant grippers. Chapter 10 devises a compliant gripper with integrated position and force sensors dedicated to automated robotic microhandling tasks. The gripper is capable of detecting grasping force and environmental interaction forces in the horizontal and vertical axes. Moreover, a variable-stiffness compliant mechanism is designed to provide the force sensing with dual sensitivities and dual measuring ranges. Chapter 11 reports a realization of the compliant gripper in MEMS scale. The gripper is driven by an electrostatic actuator and measured by a capacitive sensor. The integrated gripper possesses a compact size, less than 4 mm $\times$ 6 mm, and is fabricated using the silicon-on-insulator (SOI) microfabrication technique. The performance of the gripper is demonstrated via experimental studies.

This book provides state-of-the-art coverage of the methodology of compliant mechanisms for achieving large-range translational and rotational positioning in the context of mechanism design, analytical modeling, drive and sensing, motion control, and experimental testing. Detailed examples of their implementations are provided. Readers can expect to learn how to design and develop new flexure-based compliant micropositioning systems to realize large-range translational or rotational motion dedicated to precision engineering applications.

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Contents

1

Introduction

Abstract: This chapter presents a brief introduction of micropositioning systems and their concerned design and control problems. The compliant translational and rotational guiding mechanisms are described, the related actuation and sensing issues are raised, and the motion control problem is summarized. An outline of the remaining chapters of the book is provided.

Keywords: Micropositioning, Compliant mechanisms, Flexure hinges, Translational guiding, Rotational guiding, Actuators, Sensors, Control.

1.1 Micropositioning Techniques

Micropositioning systems refer to precision positioning devices which are capable of delivering displacement down to sub-micrometer resolution and accuracy. Micropositioning devices have been widely applied in the domain of precision manipulation and manufacturing, such as scanning probe microscopy, lithography manufacturing, and wafer alignment. To cater for the precision demands in relatively low-loading applications, flexure-based compliant mechanisms have been widely employed. Unlike traditional mechanical joints, the repeatable output motion of a flexible element is generated by the elastic deformation of the material. As a consequence, compliant mechanisms enable some attractive advantages – including no backlash, no friction, no wear, low cost, vacuum compatibility, etc. [1, 2].

According to the motion property, micropositioning can be classified into two general categories in terms of translational and rotational micropositioning. The combination of these two types of motion forms a hybrid micropositioning. Typical flexure mechanisms can deliver a translational displacement of less than 1 mm and a rotational displacement smaller than 1° within the yield strength of the materials. In modern precision engineering applications, there is a growing demand for micropositioning systems which are capable of producing large-range (e.g., over 10 mm or 10°) precision motion, yet have a compact size at the same time. Such applications involve large-range scanning probe microscopy [3], lithography and fabrication [4], biological micromanipulation [5], etc. For instance, in automated zebrafish embryo manipulation, a precise positioning stage with a long stroke is needed to execute accurate operation [6].

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In addition, a precision positioning stage with compact size allows the application inside a constrained space. For example, a compact positioning device is required to provide ultrahigh-precision positioning of the specimens and tools inside the chamber of scanning electron microscopes for automated probing and micromanipulation [7]. Moreover, a compact physical size enables cost reduction in terms of material and fabrication. Hence, this book is concentrated on the design and implementation of compact micropositioning stages with large motion ranges.

1.2 Compliant Guiding Mechanisms

Concerning the motion guiding mechanism of the positioning stage, although aerostatic bearings [8] and maglev bearings [9] are usually adopted, flexure bearings are more attractive in the recent development of micropositioning systems, due to the aforementioned merits of compliant mechanisms [10]. Compared with other mechanisms, compliant flexures can generate a smooth motion by making use of the elastic deformation of the material. Nevertheless, their motion range is constricted by the yield strength of the material, which poses a great challenge to achieving a long stroke. From this point of view, once the kinematic scheme is determined, the structural parameters of the flexure mechanism call for a careful design to make sure that the material operates in the elastic domain without plastic deformation and fatigue failure.

Given the requirements on the motion or force property, a compliant guiding mechanism can be designed by resorting to different approaches, such as the rigid-body replacement method [11], building-block method [12], topology optimization method [13], topology synthesis method [14], etc. Without loss of generality, the element flexure hinges and the translational and rotational positioning mechanisms are introduced in the following sections.

1.2.1 Basic Flexure Hinges

A basic flexure hinge functions as a revolute joint. In the literature, various profiles of flexure hinges have been used to construct a flexure stage [15]. For example, the in-plane profiles of typical flexure hinges including right-circular, elliptic, right-angle, corner-filled, and leaf hinges are shown in Fig. 1.1. More types of flexure hinges are referred to in the books [2, 16].

Referring to Fig. 1.1, if one terminal A of the flexure hinge is fixed and the other terminal B has an applied force F_x along the x-axis or a moment M_z around the z-axis, an in-plane bending deformation of the hinge will be induced. Generally, these element flexure hinges are considered as revolute joints, which deliver a rotational motion of the terminal B with respect to the fixed terminal A around a rotation center. To generate a translational motion or a multi-axis rotational motion like a universal or spherical joint, multiple basic flexure hinges can be combined to construct a compound flexure hinge [17].

During the bending deformation of the element flexure hinge, the rotation center will be varied. The notch-type flexure hinge, especially the right-circular hinge, is able to deliver a rotation with smaller amount of center shift. However, this is achieved at the cost of a relatively small rotational motion range due to the stress concentration effect. In order to accomplish a large motion range, the leaf flexure hinge is usually employed due to the mitigation of the stress concentration effect. In addition, leaf flexures have been widely employed in micromechanism

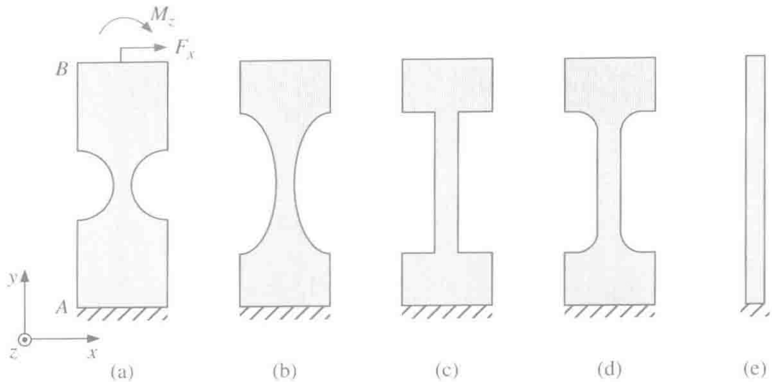

Figure 1.1 Profiles of typical flexure hinges: (a) right-circular hinge; (b) elliptic hinge; (c) right-angle hinge; (d) corner-filled hinge; (e) leaf hinge.

design in microelectromechanical systems (MEMS) devices [18]. The design methods of the beam-based leaf flexures are referred to in the book [1].

1.2.2 Translational Flexure Hinges

As a compound type of flexure, parallelogram flexure is a popular design to achieve translational motion. For example, the translational flexure hinges constructed by right-circular hinges are shown in Fig. 1.2. To generate a larger translational motion range, the translational flexure hinges can be designed using leaf hinges, as shown in Fig. 1.3.

As shown in Fig. 1.3(a), when the output stage of a parallelogram flexure translates a displacement d_x in the x-axis, it also undergoes a parasitic translation d_y in the y-axis. For some applications, the translation d_y can be employed to enhance the resolution of the displacement due to the displacement deamplification effect. Concerning a large-range positioning in the

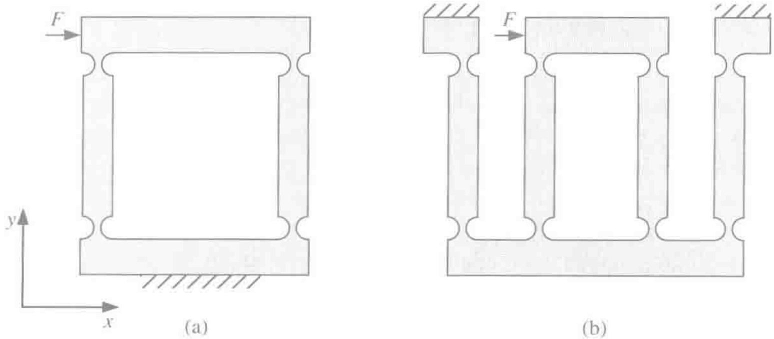

Figure 1.2 Translational flexure hinges constructed by right-circular hinges: (a) parallelogram flexure; (b) compound parallelogram flexure (CPF).

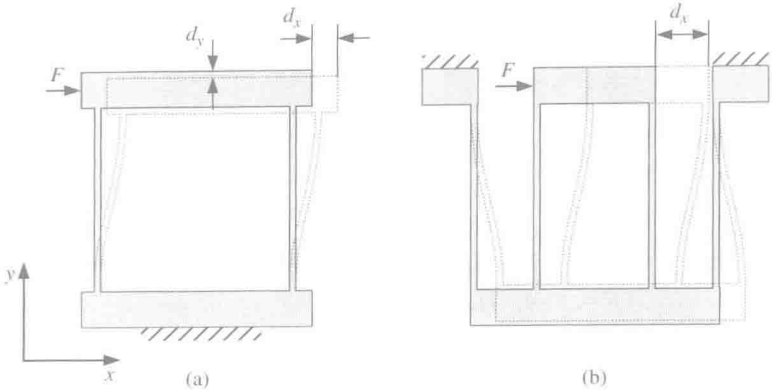

Figure 1.3 Translational flexure hinges constructed by leaf hinges: (a) parallelogram flexure; (b) compound parallelogram flexure (CPF).

specified direction, the parasitic translation d_y is unwanted. In order to obtain a larger straight motion while eliminating the parasitic translation, a compound parallelogram flexure (CPF), as shown in Fig. 1.3(b), can be employed.

Intuitively, a longer stroke can be realized by using a longer and more slender leaf flexure. However, in practice, the length of the flexure hinge is constrained by the requirement of compactness and the minimum width is restricted by the tolerance of the manufacturing process. It is challenging to design a flexure micropositioning stage with a large stroke and compact size simultaneously. To overcome the aforementioned problem, the concept of multi-stage compound parallelogram flexure (MCPF) [19], as shown in Fig. 1.4(a), is employed in this book.

Compared with conventional CPF, the motion range of a MCPF is enlarged N times without changing the length and width of the flexures, where N is the number of basic CPF modules. Note that CPF is a special case of MCPF with $N = 1$. To enhance the transverse stiffness in the y-axis direction, an improved MCPF is presented as shown in Fig. 1.4(b), which is constructed by connecting the two secondary stages together.

1.2.3 Translational Positioning Mechanisms

A translational positioning mechanism is usually required to provide the translational motion in the two-dimensional plane or three-dimensional space. To generate the translational positioning in more than one direction, a suitable mechanism design is necessary. As far as a kinematic scheme is concerned, the positioning stages, which are capable of multi-dimensional translations, can be classified into two categories in terms of serial and parallel kinematics. The majority of the commercially available stages employ a serial-kinematic scheme. For example, some micropositioning stages have been developed by stacking the second single-axis positioning stage on top of the first one or nesting the second stage inside the first one [20–22]. In this way, the entire second stage is carried by the first one, as illustrated in Fig. 1.5(a), where the X stage serves as the output platform of the XY stage. As an example, the computer-aided design (CAD) model of a serial-kinematic XY stage is shown in Fig. 1.6(a), where the parallelogram flexures are constructed using right-circular hinges.