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A Large Range Flexure-Based Servo System Supporting Precision Additive Manufacturing

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ABSTRACT

This paper presents the design, development, and control of a large range beam flexure-based nano servo system for the micro-stereolithography (MSL) process. As a key enabler of high accuracy in this process, a compact desktop-size beam flexure-based nanopositioner was designed with millimeter range and nanometric motion quality. This beam flexure-based motion system is highly suitable for harsh operation conditions, as no assembly or maintenance is required during the operation. From a mechanism design viewpoint, a mirror-symmetric arrangement and appropriate redundant constraints are crucial to reduce undesired parasitic motion. Detailed finite element analysis (FEA) was conducted and showed satisfactory mechanical features. With the identified dynamic models of the nanopositioner, real-time control strategies were designed and implemented into the monolithically fabricated prototype system, demonstrating the enhanced tracking capability of the MSL process. The servo system has both a millimeter operating range and a root mean square (RMS) tracking error of about 80 nm for a circular trajectory.

1. Introduction

Micro-additive manufacturing (micro-AM) is considered to be an effective method to improve the performance of three-dimensional (3D) microproducts. Scalable AM is classified as one of the main groups of micro-AM, and includes stereolithography (SL), selective laser sintering (SLS), and inkjet printing; these technologies can be employed at both the macroscale and microscale in order to efficiently fabricate complex 3D components.

As one of the most popular scalable AM technologies, SL solidifies a liquid polymer by photo-curing with high resolution. Micro-stereolithography (MSL) [1–3] is SL at the microscale, and is widely used in many areas, such as microsensors [4], optical waveguides [5], 3D photonic band gap structures [6], and biology analysis [7]. During an MSL process, a two-dimensional (2D) microscale pattern is formed by solidifying a liquid photopolymer; next, a 3D structure can be obtained by accumulating the 2D patterns. An MSL system is mainly composed of a liquid resin container and a precision multi-axis motion stage, with which the patterns are accurately located with the laser beam in order to solidify the resin.

The accuracy of the finished product is determined by both the solidified area generated by the light beam and the motion quality of the positioning system. In other words, the motion system must be accurate and repeatable enough to reach the right location for every solidification event. A considerable amount of research effort has been devoted to reducing the laser spot size; examples include Refs. [8–10] and the references therein. However, relatively fewer works emphasize the motion quality of positioning systems, possibly

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because the required motion quality corresponding to the laser spot size is not particularly stringent. Given the recent decrease of the laser spot size down to 1 μm or less [10], the corresponding motion quality should be one order of magnitude less than the laser spot size—that is, < 100 nm. This means that a nano precision stage is required in order to achieve nanometric motion quality. In order to achieve such a high-precision motion quality, the choice of the bearings of the motion stages is crucial. Most current multi-axis positioning stages are based on contact bearings, such as linear guideways, which limit the motion quality to the sub-micrometer level; moreover, this type of design requires sophisticated assembly and maintenance.

With the goal of providing a nanopositioning system to support MSL systems, this paper discusses the development of a beam flexure-based motion system. To overcome the abovementioned disadvantages of contact bearings, it is desirable to have a motion system that uses frictionless bearings. Flexure bearings provide motion by means of the elastic deformation of flexures, which allows nondeterministic effects such as friction, backlash, and wear to be avoided during the operation; as a result, nanometric motion quality can be achieved in a compact desktop size. Furthermore, beam flexure-based nanopositioning systems are extremely suitable for harsh operation environments, as zero maintenance is required. By combining multiple beam flexures, a flexure mechanism can be constructed to provide millimeter-range (or even centimeter-range) motion guidance and load bearing in a compact desktop size [11,12]. Despite the abovementioned advantages of flexure bearings, some challenges still exist in the design and control of beam flexure-based nanopositioning systems. In research into the development of over-millimeter-range *XY* micropositioners (e.g., Refs. [12,13]), the actual motion quality of these systems were not fully satisfactory, with very few experimental results showing nanometric tracking accuracy (< 100 nm). As one of the aims of this work, we would like to emphasize mechanism design and real-time control strategies in order to show the nanometric tracking accuracy of large range beam flexure-based nanopositioner supporting MSL systems.

The remainder of this paper is organized as follows: In Section 2, the design of a large range beam flexure-based nanopositioning stage is discussed, with detailed finite element analysis (FEA) and verification. In Section 3, a real-time control system is proposed for trajectory tracking of the nanopositioning system, and in Section 4, numerous experiments are conducted on the fabricated prototype system to demonstrate the desired ability of the nano servo system.

2. A beam flexure-based nanopositioning stage supporting MSL systems

A schematic design of a beam flexure-based MSL system is shown in Fig. 1. The main components of the MSL system and their features are briefly introduced. A light source and a related optical system are responsible for generating a small laser beam (with a spot size of < 1 μm) to induce photo-curing. For the sake of compact size, a Blu-ray optical pickup unit (OPU) can be chosen as the light source [14]. The multi-axis motion system is mainly composed of two positioning stages. One is an *XY* nanopositioning stage; this is the key to precisely locating the laser beam in an *XY* plane, such that the *XY* cross-sections of a 3D micro component can be solidified. When the laser spot size goes down to 1 μm or less, a nanometric motion quality of the *XY* motion stage is required. The development of such a nanopositioning system in a compact desktop size is challenging and is the main concern of this work. The other positioning stage is a *Z*-axis translator, which is responsible for providing the required vertical motion of one layer thickness of the sliced 3D component. Since the motion quality of the *Z*-axis translator is at the micrometer level, this solution is widely available and hence is not under consideration in this study.

With the abovementioned motion requirement in mind, we present a compact beam flexure-based nanopositioning stage supporting MSL system. To be specific, an *XY* nanopositioning stage was designed to locate the laser beam in a range of 3 mm along both *X* and *Y* axes. For this range, electromagnetic actuators such as voice coil actuators (VCAs) are usually adopted to provide thrust forces.

Instead of obvious but bulky serial kinematic configuration of the *XY* positioning stage, in which one axis stacks on top of another, we considered a parallel kinematic configuration of the flexure mechanism, in which each axis actuator is grounded mounted. With this type of configuration, a higher bandwidth and precision of the motion system can be achieved due to the lack of moving actuators and disturbance from moving cables, respectively. Furthermore, in order to achieve a millimeter range and nanometric motion quality of the *XY* parallel mechanism, it is necessary to carefully manage parasitic error motions, which are the motions in any axis that differ from the axis of an applied thrust force. With the increase of the stroke, the in-plane parasitic error motion of the moving stage also increases, including parasitic translational and rotational motions, both of which significantly adversely affect the nanometric motion quality. To reduce the parasitic motions, a mirror-symmetric arrangement is desired, and appropriate planar redundant constraints are usually required in order to reject various disturbances.

Fig. 2 shows a conceptual design, in which the Z-shaped and Π-shaped parallelogram beam flexures provide the required load bearing and kinematic decoupling, and the four-beam flexure serves as the redundant constraints to improve the disturbance-rejection capability of the mechanism. As shown in later sections, the important

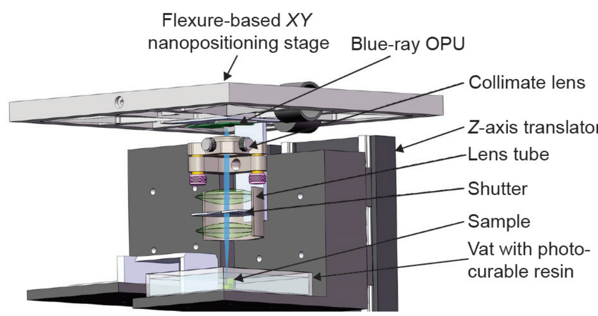

Fig. 1. Schematic design of a beam flexure-based MSL system.

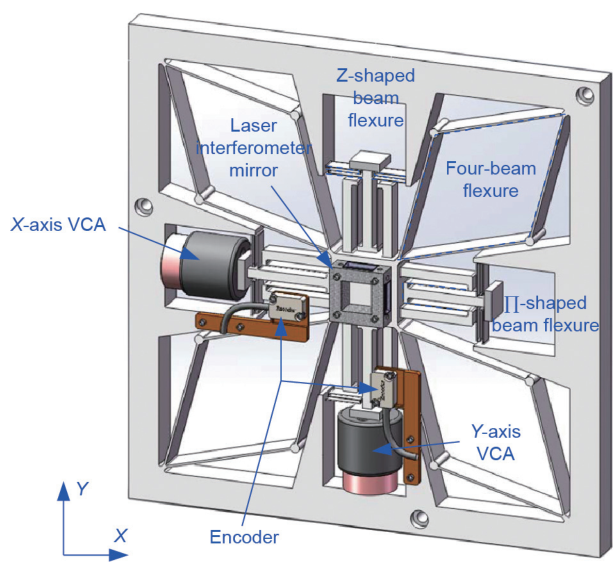

Fig. 2. A large range beam flexure-based *XY* nanopositioner.