



Design and analysis of a compact flexure-based precision pure rotation stage without actuator redundancy



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ABSTRACT

This paper presents the mechanical design, optimisation, and computational and experimental analyses of a flexure-based single degree of freedom rotation stage. The mechanism possesses a rotationally symmetric configuration, whilst only employing a single piezoelectric actuator, which increases the mechanism's ability to reject cross-coupled drift of the rotation centre. This layout is facilitated by a novel multi-level structure, which exploits emerging additive manufacturing techniques for its construction, and is compact, with little unused volume. Computational analysis has been employed for both the optimisation of the mechanism, to increase its workspace whilst maintaining a small physical footprint, and subsequently to predict its performance. The cross-coupled drift, particularly its variation with respect to assembly and manufacturing errors, is explored in depth. A prototype has been manufactured, which fits within a 128mm×153mm×30mm bounding box, and its working range has been experimentally determined to be 2.540mrad, with a first natural frequency of 175.3Hz.

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1. Introduction

Compliant mechanisms have emerged as fundamental components within many emerging devices in nanotechnology, including inside scanning probe microscopes (SPM), high-density data storage, and manipulators for micro-manufacturing, assembly and biohandling applications [1–5]. Their applicability for these tasks is drawn from their ability to produce smooth, continuous motions, free of backlash and other non-linear effects which inhibit the use of conventional joints.

Various designs have been proposed to facilitate the production of ultrahigh precision motions, particularly with regard to translational positioning. Whilst scanners have been developed which produce linear motions with one, two and three degrees of freedom (DOF), the majority of existing research has focused on two DOF scanners, due to their applications within SPM and nano-imprint lithography [6–10]. The demands of high-dexterity manipulation tasks and optical alignment have led to the

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requirement for positioners also possessing angular axes of motion. Recent research efforts have led to the development of positioners with two to six DOFs, all including at least one angular motion axis [11–15].

Many different modes of actuation have been employed to provide the necessary input to these mechanisms. These include voice coil motors, electrostatic drives, thermal actuators and magnetic actuators. Within existing literature, the piezoelectric actuator (PEA) is most commonly favoured, due to its high resolution and compact size. However, PEAs exhibit a rate-dependent hysteresis effect, with its magnitude being a significant proportion of the full stroke at high frequencies, as well as drift in their response. For this reason, almost all PEA-driven nanopositioners employ a combination of feedforward and feedback control in practice. Typically, feedforward strategies employ inversions of the modelled PEA hysteresis [16–18], before the feedback component works to eliminate residual errors and maintain robustness to instability [19–22].

The objective of the study presented in this paper is to produce a compliant pure rotational scanner with the largest possible angular range, which minimises the cross-axis coupled drift of the rotation centre, whilst only being driven by a single actuator. The stiff structure of PEA-driven compliant mechanisms allows them to exhibit high motion bandwidths, and they are capable of large output forces [23, 24]. However, due to the PEA's limited stroke, the mechanism must be optimised to maximise the output range, subject to constraints on the maximum mechanism size. Such a mechanism would have applications within optical steering, calibration and workpiece alignment tasks [25–27].

Cross-coupled drift of the rotation centre during motion would detract from its performance. An integral strategy for minimising drift is the incorporation of rotational symmetry within the design of the mechanism and its actuation. In particular, if the mechanism were designed with two-fold rotational symmetry about its centre (invariance to a rotation by 180°), then any translation within an output motion must be invariant to this rotation. Therefore any cross-coupled translation is necessarily eliminated within these ideal conditions.

A key objective within the design of the mechanism is the elimination of actuator redundancy – the use of only one actuator to actuate the single motion axis. Manufacturing processes such as wire electrical discharge machining (WEDM) typically limit positioner designs to lie within a single plane, and subsequently such rotational scanners must have two or more actuators to allow for symmetry in the design. In this case, particularly if PEAs are employed, the reduction of cross-coupling cannot be guaranteed. As a result of the unknown and possibly unequal level of hysteresis, uneven preloads, mounting defects and manufacturing imperfections, there will be an inevitable difference between the two displacement inputs, breaking the rotational symmetry and leading to a coupled translation in the output.

Frontier additive manufacturing technologies, such as fused deposition modelling (FDM) and stereolithography, are increasingly providing higher resolution fabrication capabilities from a broadening set of materials. In this paper, such techniques are exploited to free the mechanism from being constrained to a single plane. This further allows the use of a single actuator, whilst maintaining the requisite symmetry.

A pure rotation scanner has previously been designed by Lee et al. [28]. However, this mechanism employed two PEAs, and also did not possess rotational symmetry in its design; making it susceptible to drift of the rotation centre. Cathie and Janky also proposed a flexure-based rotation stage, however, a method of actuation was not provided [29]. Planar XY θ positioners could also be utilised for this purpose, however this would require added consideration of actuation, sensing and feedback schemes for the linear axes to compensate for drift.

The remainder of the paper is structured as follows: in Section 2 the design of the mechanism, and its subsequent optimisation, are provided. Section 3 details a computational examination of the optimised design, with a focus on the working range and undesirable cross-coupled motions, and their variation as manufacturing errors are introduced. Results from experimentation performed on a manufactured prototype are presented in Section 4. Finally, considerations for practical implementations are discussed in Section 5.

2. Mechanism design

Fig. 1a shows a rigid body schematic of the underlying amplification structure for the proposed rotational scanner. The principal design element is the four bar crank-rocker mechanism, from which the output rotation is taken to be at the crank-base joint. An input lever provides amplification to the vertical input, whilst also ensuring that the input is horizontally aligned with the output hinge. The rigid body equivalent to the compliant mechanism is immobile due to this lever.

Rotational symmetry of the design is achieved by the addition of a duplicate of the underlying structure, which replaces the output hinge. The duplicate is rotated by 180° about the output point, as illustrated in Fig. 1b. With a symmetric input, the output rotation is then centred on the crank linkage.

Fig. 2 shows the compliant design basis of the proposed rotational mechanism. The mechanism has been separated into two levels: the upper level provides the functionality of the schematic in Fig. 1, whilst the lower level provides the symmetric inputs to the upper level. The input bridge amplifier stage of the lower level transforms the expansion of a PEA into transverse motions to be transferred to the upper stage. In particular, the two double parallelogram linkages of the input stage ensure that the PEA is not exposed to shearing forces.

Due to the duplication of the structure to achieve the symmetry of the design and the removal of the flexure hinge, the output link has an added (translational) degree of freedom when the input is fixed. As a consequence, undesirable vibrational modes exist at low frequencies, which are discussed within the computational analysis in Section 3. To remedy this, cantilevers have

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