A Dual Stage Compliant Positioning System with Integrated Planar Optical Grating for Position Feedback

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Abstract

Assembly, handling and dispensing systems for small-scale parts play an essential part in reducing the cost of these products. These operations require both long coarse positioning for transfer between operations as well as dispensing as well as fine short range positioning on the submicron level for feature assembly. Typical prismatic rolling guide-way based positioning stages with ballscrew drives are to inaccurate for positioning in the submicron level which led to the development of dual stage positioning systems [1]. One stage performs the coarse long-range motions whereas another stage provides small precise motions. One disadvantage of such systems is that each actuator requires individual motion feedback, which leads to higher system cost. Focus of this paper is the design of a positioning stage that uses a dual stage approach for coarse and fine positioning, but utilizes a single two-dimensional optical grating interferometer as position feedback for the resultant motion feedback. This results in significant reduction in error sources and measurement uncertainties due to misalignment and measurement system errors.

Keywords: Micro assembly; Optical position feedback; Friction drive

Introduction

Positioning stages with nanometer accuracy can be designed using compliant mechanisms and piezo actuators, however their travel range is very limited. Therefore if the travel range goes beyond several millimeters a dual approach is pursued. However this approach is much more costly since it requires additional sensors and actuators. The use of individual displacement sensors for each stage leads to an increased error budget. In addition a single reference coordinate frame is not available which decreases the repeatability of the system [2, 3]. This paper introduces a combination of a friction drive for the long range travel, and a conventional flexure stage for the perpendicular travel. Unique to this approach is that a single two degree of freedom optical encoder with a grating scale is used. The longer-range positioning stage with a motion range of 200mm is a conventional linear guide way system. It has an optical grating mounted in the center neutral plane of the stage (Figure 1). This prevents the influence of bending forces on the optical grating. The optical grating has an optical resolution of 4 nm by means of interpolation of the 4 micrometer grating pitch. The optical grating is rigidly attached along the guide-way to provide a reference coordinate system.

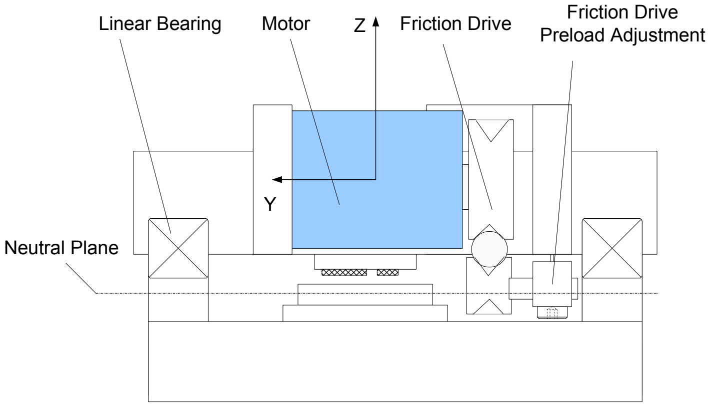

Figure 1: Schematic of the friction drive.

The drive system consists of a vee roller friction drive [4] that allows for very fine positioning. The friction drive has a driven stage that includes the motor and a stationary drive rod for traction. This configuration has the advantage of smaller footprint and the possibility of multiple drives on one stage for parts transfer. A disadvantage is the increased inertia of the moving system, which has an influence on the acceleration and deceleration curve of the drive. However once the system is tuned the system performs robust since the payload is typically small compared to the small scale part weight.

To increase the accuracy and repeatability of the system the drive system is decoupled via a flexure, and directions other than the driven direction are weak (Figure 2).

The second stage for small precise motions of up to 1mm in y direction consists of a flexure system for slip stick free motion. This off the shelf flexure stage has a two direction sensing optical encoder attached to the moving platform that measures the relative position of the flexure stage versus the optical grating along the guide way in x and y direction.

Friction Drive Design

The vee roller friction drive is sized along the following requirements:

- Maximum displacement precision dl for the encoder resolution dE and the wheel Radius R
- Limiting acceleration a based on mass m, the friction μ, and the preload P
- The desired and achievable rectilinear velocity V
- The tangential stiffness of the drive F_t based on the mindlin formula
- Maximum allowable contact stress σ dependent on the contact area A

$$dL = 2 \cdot dE \cdot Pi \cdot R \tag{1}$$

$$a = \frac{F \cdot \mu}{m} \tag{2}$$

$$V = R \cdot \omega \tag{3}$$

$$\sigma = \frac{F}{Pi \cdot A} \tag{4}$$

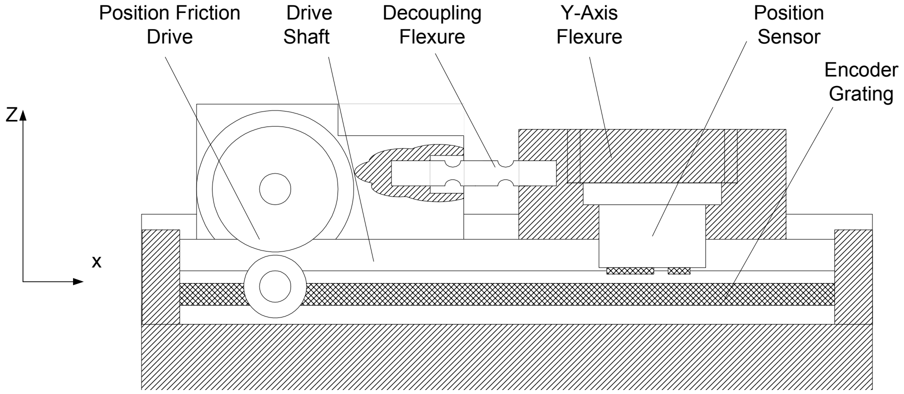

Figure 2: Schematic of the friction drive and the positioning unit.

Connecting Flexure

The connecting flexure is designed to provide a bending stiffness that is lower than the bearing stiffness of the driven slide.

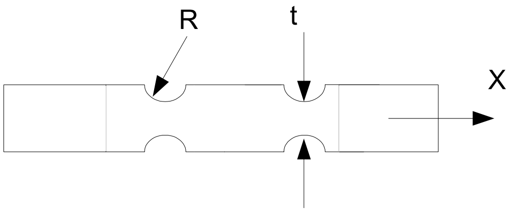

Figure 3: Parameters of the compliant link.

The compliant link stiffness can be calculated for axial, torsion and bending stiffness:

Axial Stiffness: $$k_a = \frac{Et^{3/2}}{20R^{1/2}} \qquad (5)$$

Torsion Stiffness: $$\phi = \int_0^L \frac{Tdx}{GI_{px}} \qquad (6)$$

Bending Stiffness: $$k_b = \frac{Et^{7/2}}{20R^{3/2}} \qquad (7)$$

The parameter G is the shear modulus, T is the applied moment and I_{px} the polar moment of inertia that varies over the length L

Position Feedback and Error Compensation

The Grating of the planar encoder with a length of up to 200mm and a width of 20mm is glued on the stainless steel stage surface. Since the stage is assembled and operated in a controlled environment the thermal behavior of the is stable. The heat generated by the motor is decoupled via the compliant link. The optical read head is mounted to the flexure stage. The errors due to mounting of the grating and of the optical grating can be greatly reduced if a laser interferometer is used. The straightness and translation errors of the stage are measured and compensated via a position dependant polynomial scheme for off axis errors and a lookup table for on-axis errors that resides in the control system [4]. Grating encoders as well as laser interferometers use two sinusoidal waveforms as out put of their photo detectors as representation of position and direction. This signal is commonly 1Volt Peak to Peak. The following errors can occur in this representation:

- A DC offset in either sinusoidal waveform DC
- A phase offset Ph
- A deviation in the amplitude between both signals.
- A shape error of the signal
- An error in the actual grating pitch

Typically the shape of the sinussoidal signals is represented in a lissajou figure in which a dc offset will result in a center offset of the figure in either x or y direction and a phase error will result in an inclined circle. If the amplitude relationship of both signals is off an “egg” shape results. Heydemann et al presented an software compensation scheme, which has been implemented in commercial systems. But these calculations lower the sampling time of the data acquisition. Therefore in this system the electronics is tuned to provide a high resolution. Table one shows allowable interpolation error values for the grating with 4micrometer grating pitch as target. Please note that these errors are not accumulative.

Error Source	Error in Degree	Error in %	Interpolation Error [µm]
Amplitude mismatch		2	0.006
Phase error	0.5		0.003
Shape error		0.1	0.004
DC offset	0.5		0.003
Resulting error			0.010

Table 1 shows the adjustment specification for a interpolation error of less than 10nm.

Figure 4 shows the output signal of the encoder, and its resulting lissajou figure. The values are based on the error values in column 2 and 3 of table 1, and the resulting interpolation error in micrometer.

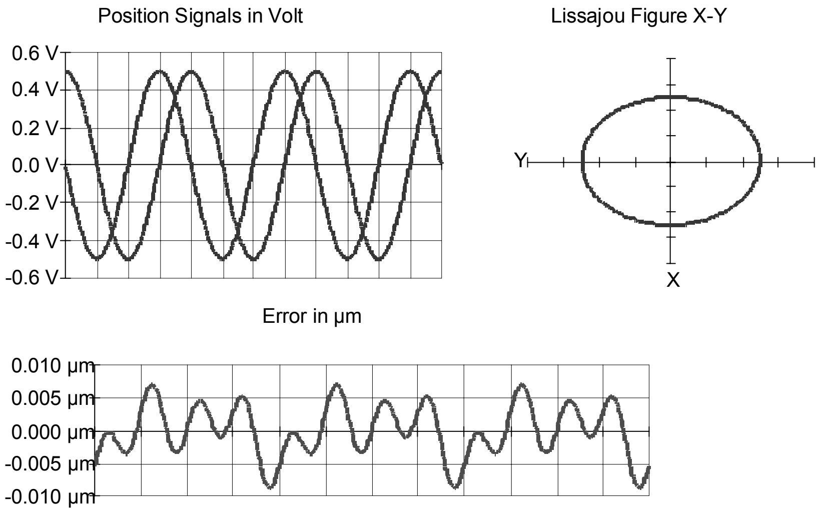

Figure 4: The lissajou graph and the interpolation error caused by signal errors of table 1.

Control Concept

The control uses conventional PID servo control for both axis, however an x-axis lookup table for enhanced accuracy is added as well as the polynomial compensation as function of the traveled length x is added. Inorder to avoid slip the acceleration curve is adjusted and the torque command is limited below the slip torque.

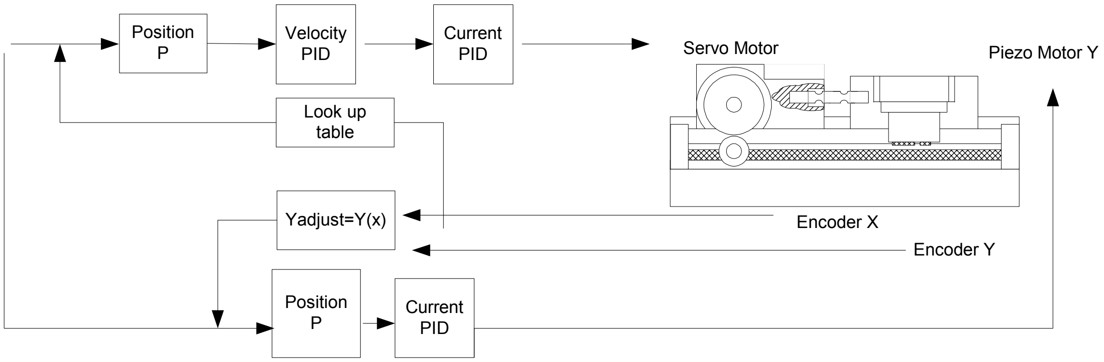

Figure 5: The control schematic for the stage

Conclusion

The design approach for a dual positioning friction drive stage was shown and the associated feedback system error compensation was introduced. A control method for reliable high precision positioning was also presented. This design approach will be verified in a future laboratory study on the finalized Stage.

References

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