

Linear Motion Carriage Driven and Guided by Elastically Supported and Preloaded Lead Screw Nuts

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Abstract -

The quest for low cost precision machinery benefits developing nations and can open new markets. The principles of elastic averaging can fulfill the need for low cost precision machinery while maintaining a large degree of accuracy and repeatability. In this paper, a linear carriage was constructed, built, and tested using readily available industrial construction supplies. Elastic averaging was achieved by two hex nuts preloaded via flexures on a threaded rod. The prototype maintained accuracy and repeatability to better than 25 microns in the carriage's six degrees of freedom. These results are consistent with the postulations of a kinematic error model performed on the carriage design and suggest a wide variety of applications for the concept.

keywords – *linear motion, elastic averaging, low cost, lead screw*

Introduction

The first precision machines used lead screws whose nuts were preloaded either with a split nut or by using a leather nut, and the straightness error in the screw shaft was isolated from the carriage by means of a coupling [1]. Since then, the goal has been similar: use preload to minimize the effects of backlash, and isolate the nuts from the carriage. However, the task of creating preloaded precision linear motion bearings still remains. In the quest for lower cost precision machines, for use by small shops or the developing world, we can return to fundamental principles of elastic averaging [2] and use these to enable the creation of low cost precision machines. In such applications an accuracy one-half millimeter or better is desirable. Accordingly, this paper introduces the concept of using two low cost rolled threaded rods as the guidance rails and actuators for a linear motion axis. Preloaded nuts are mounted on the rods. One nut serves as the master against which all others are preloaded using flexural bearings. Due to the angled geometry of the threads on the rod, this means that all six degrees of freedom are in effect preloaded, and a high degree of repeatability is obtained. Furthermore, by using additional nuts preloaded against the master nut by flexures, a greater degree of accuracy could be obtained through the mechanism of elastic averaging.

Figure 1 shows the prototype system that was designed, built, and tested. This single axis apparatus consists of a precision linear carriage actuated by two RH 1"-14 threaded rods coupled to each other with pulleys and a timing belt. Using two threaded rods eliminates the need for costly bearings and places the actuation forces along the centers of stiffness. This configuration helps reduce binding and load-induced errors. The linear carriage is coupled

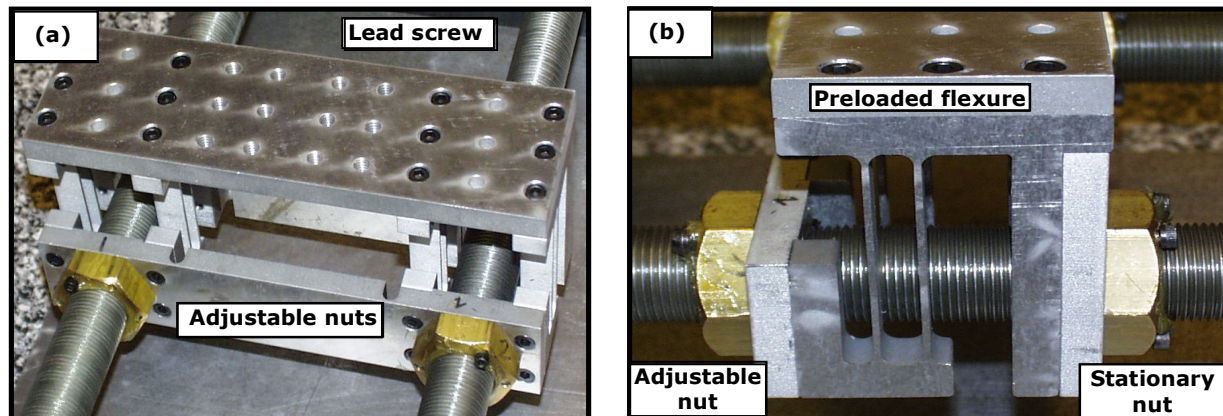


Figure 1 (a) Prototype system built using simple construction materials (b) Nuts preloaded via flexures

to the threaded rods through four brass hex nuts, two per rod. Preload is provided by flexures between the nuts. The rolled threaded rods were obtained from a construction supply vendor, and are typical of threaded rod used the world over in construction projects. The brass nuts were turned on one end to form a round section, which fit into a bore in the end plates of the carriage. The flexures are preloaded by rotating and then locking the nuts in place using socket head cap screws. The flexures were cut using an OMAX 2626 abrasive waterjet machining center [3]. This

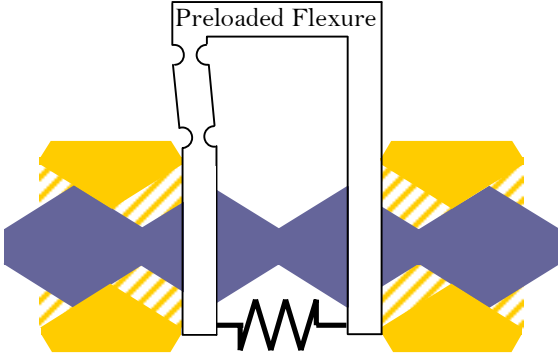


Figure 2 Concept of self-centering nuts under preload

simple system cost less than \$50 in materials and represents a cost savings of two orders of magnitude or more over conventional precision carriages.

Besides cost advantages, the industrial grade components used provide the necessary tolerances to allow for self-adjustment. In normal applications, the clearance inherent in these components is undesirable, if not detrimental, to the system. Our design uses this clearance to its advantage. By preloading the hex nuts on the threaded rods, they self-center against the 60-degree thread form, resulting in more accurate and more repeatable carriage control. This self-centering action continues until the flexures find their lowest energy states; a state which occurs at the minimum deflection of the flexure as shown in Figure 2. The clearance between the rods and the nuts also reduces the possibility of binding.

For the experiment contained in this paper, only two nuts per rod were used to obtain the desired elastic averaging effects. However, as more flexured nuts are added to the mechanism, the accuracy and repeatability will increase [2]. In this configuration, the master nut anchors the position of the carriage, while the flexured nut provides the preload.

To ensure elastic averaging, the preload exerted on the nuts must be larger than opposing counter forces. Thus, the weight of the carriage must be controlled. A simple balance of forces at the interface of the nut and the threaded rod, including frictional effects, can be summarized as

$$F_{preload} \cos \theta > w \sin \theta + \mu (w \cos \theta + F_{preload} \sin \theta), \quad (1)$$

or alternatively,

$$F_{preload} > \left(\frac{\mu \cos \theta + \sin \theta}{\cos \theta - \mu \sin \theta} \right) w. \quad (2)$$

Here w represents the weight of the carriage applied to each nut, $F_{preload}$ is the preload force, θ the incline angle of the threaded form, and μ the coefficient of friction between the steel rod and the brass nuts. The outcome of Equation (2) as applied to the experimental system in this paper is

$$F_{preload} > 2.865w. \quad (3)$$

Consequently, a preload of 100N was applied to the hex nuts to overcome the weight of the carriage (14.6N). The 100N preload was more than sufficient because the weight of the carriage is spread over four preloaded nuts.

Kinematic Error Model

A kinematic error model was developed to estimate the accuracy and repeatability of the prototype system. The proposed experimental design, shown in Figure 3, forms a closed structural loop between the support frame and the rolled threaded rods with the linear carriage stacked on top of this loop. In order to simplify the model, the entire

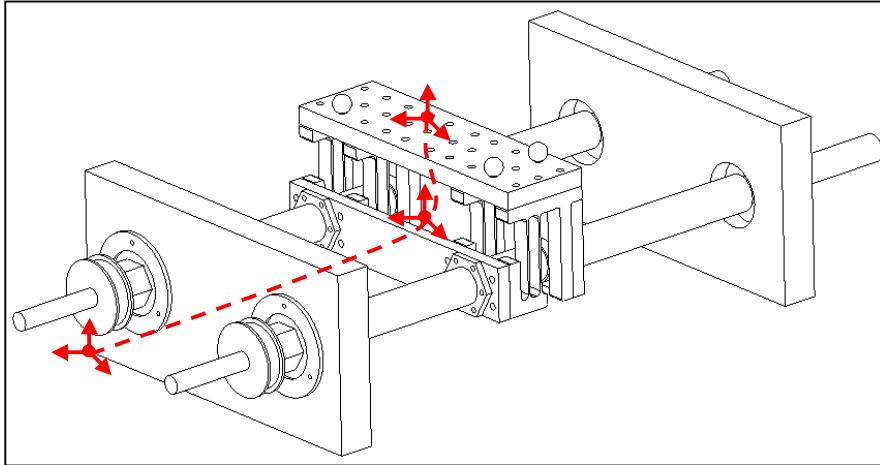


Figure 3 Proposed design illustrating error budget coordinate reference frames

system was analyzed in an open structural loop form. A coordinate system reference frame placed in the middle of the threaded rods with estimated translation and rotation errors takes into account the aforementioned closed structural loop. Prominent errors included in this error budget analysis were radial and axial play in the threaded rod bearings, manufacturing errors in the threaded rods and brass hex nuts, machining errors in the prototype system components and misalignment of assembled pieces. The estimated errors

and coordinates of the component reference frames were placed into an error gain matrix spreadsheet in order to calculate the resulting accuracy and repeatability of the carriage's 6 degrees of freedom [4]. All of the manufactured components were machined using the OMAX 2626 abrasive waterjet machining center and a Bridgeport EZTRAK I CNC milling machine [5]. This resulted in machining tolerances to within +/- 76 microns, which were used as a guideline for calculating the systematic errors in the kinematic error model.

Experimental Setup

In order to evaluate the performance of the prototype, an experiment was designed and conducted using a coordinate measurement machine (CMM), which is accurate to approximately 5 microns [6]. The linear motion axis was clamped to the CMM table and measurements were taken at intervals of fourteen rotations (approximately 25.4mm or 1" of linear travel). Three spheres were bonded to the motion carriage and measured at each position to calculate both translational and rotational error motions. All measurements were taken in a static condition with the threaded rods rotated to exactly the same position, give or take one degree, or about two ten thousandths of an inch error motion in the axial direction. This testing configuration eliminated the effect of several of the prototype's systematic errors.

Measurements were taken at eleven locations with the carriage moving in the positive axial direction (forward) and then taken at the same eleven locations with the carriage moving in the negative axial direction (backwards). Each of these locations was fourteen turns apart resulting in approximately 25.4cm or 10" of total travel.

Results

The experimental results of the prototype were extremely encouraging. The original goal of an accuracy and repeatability of around one-half millimeter was easily met. At worst, the prototype was accurate to approximately 10 microns in the transverse (x) (Figure 4) and axial (y) directions (Figure 5), and to within 25 microns in the vertical (z) direction (Figure 6).

The repeatability was equally impressive with error in the vertical direction of less than 15 microns, and error in the transverse and axial directions of less than 10 microns. Table 1 lists the accuracy and repeatability measures at each position along the threaded rod. Additionally, all rotational error motions were less than five ten thousandths of a radian.

It is important to note that the accuracy is computed after taking into account a best linear fit calibration of the individual data sets relative to the reference frame.

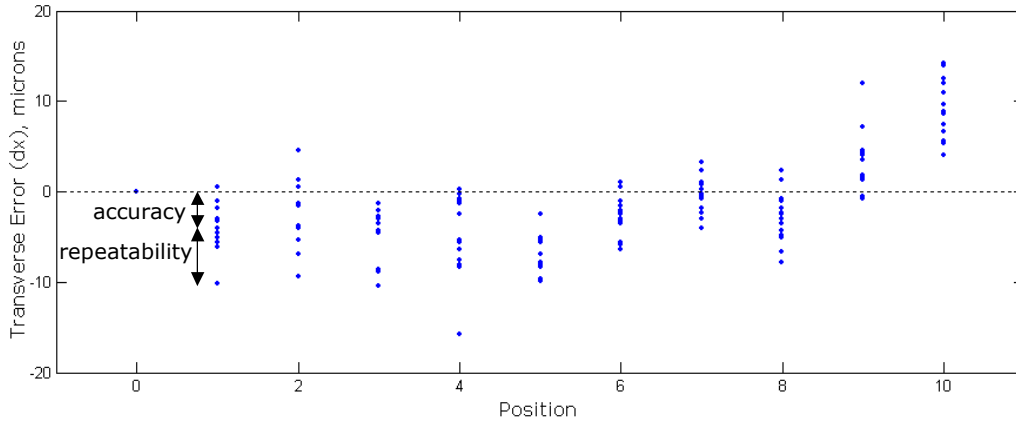


Figure 4 Linear fit of transverse error vs. position (position markers spaced 25.4mm apart)

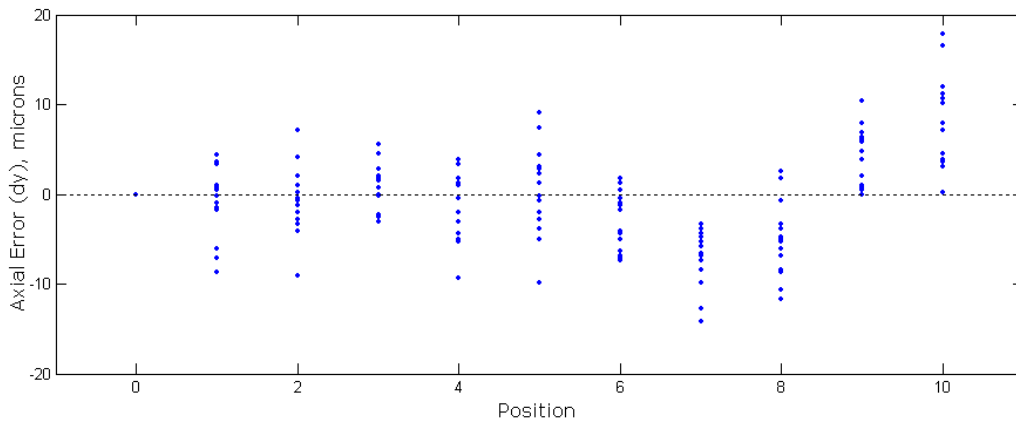


Figure 5 Linear fit of transverse error vs. position (position markers spaced 25.4mm apart)

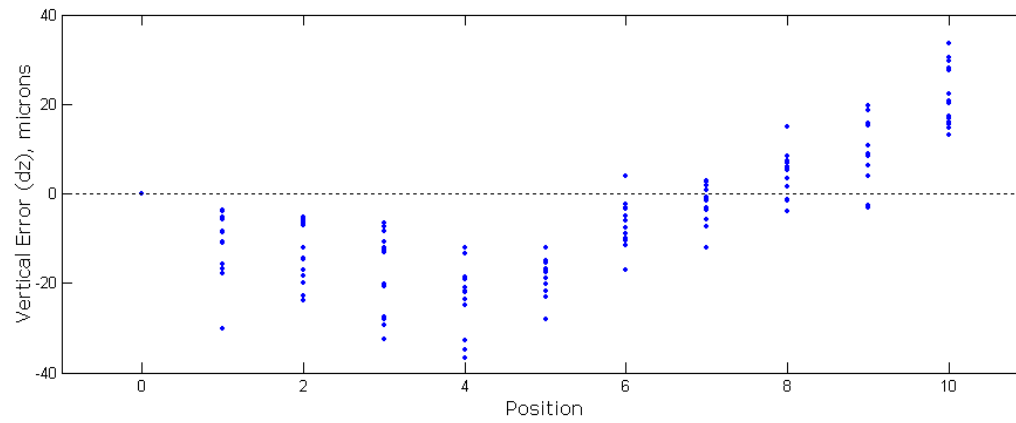


Figure 6 Linear fit of vertical error vs. position (position markers spaced 25.4mm apart)

The original data showed clear linear trends indicating that the measurement axes and the actual motion were not aligned. A simple linear correction was applied to obtain the above data, simulating a calibration movement aligning the motion axes to the reference frame. In the transverse and vertical directions this was a rotation of the reference frame due to misalignment. In the axial direction the linear correction was for thread inaccuracy

(approximately 1.00145” per 14 turns). The remaining error is most likely due to bearing error motions, straightness and other manufacturing errors in the threaded rod, as well as deflection of the threaded rod in the center of the range of motion. This deflection error can be clearly seen in Figure 6. Unlike the accuracy error, the repeatability error did not display many clear trends.

Position	Accuracy			Repeatability		
	dx transverse	dy axial	dz vertical	dx transverse	dy axial	dz vertical
0	-	-	-	-	-	-
1	-3.8	-1.4	-11.3	5.4	6.5	13.4
2	-2.8	-0.8	-12.9	7.1	8.1	9.2
3	-6.1	1	-18.4	4.7	4.2	13
4	-4.9	-1.5	-23.3	8	6.7	12.5
5	-7.1	0.4	-18.7	3.7	9.5	8
6	-2.8	-3	-7.1	3.7	4.6	10.5
7	-0.5	-7.7	-2.2	3.7	5.5	7.3
8	-2.8	-5.1	3.7	5.2	7.1	9.5
9	3.5	4	9.9	6.4	5.3	11.3
10	9.4	8	21.9	5.1	8.8	10.2

Table 1 Accuracy and repeatability at each position (in microns)

Conclusions

The results of the prototype prove that low cost rolled threaded rods can be used to drive a repeatable linear axis using preloaded, elastically averaged nuts. Table 2 compares the results of the kinematic error model and the experimental results to the original functional requirements. The implications of these results lend themselves to many applications where ultra high precision is not necessary. In these cases a low cost alternative would be most viable. Small shops, developing countries, and non-traditional industries may most benefit from this technology in the immediate future.

		Functional Requirement	Prototype Kinematic Error Model	Prototype Experimental Results
Accuracy	dx	500	(±) 58	+9.4/-7.1
	dy	500	(±) 37	+8.0/-7.7
	dz	500	(±) 25	+21.9/-23.3
Repeatability	dx	±500	±30	±8.0
	dy	±500	±22	±9.5
	dz	±500	±16	±13.4

Table 2 Error budget and experimental results for worst cases (all units in microns)

Further improvements can be made using one LH threaded rod and one RH threaded rod for actuation to cancel torques created on the carriage. Similarly, lining up the natural bow of the threaded rod can lead to improved accuracy and repeatability. Other variants include elasticity within the nut threads themselves as suggested by an engineer at Polaroid or elasticity in the nut diameter.

References:

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