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Design and construction of a fine drive system for scanning optical elements

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Abstract

The design and operation of a simple mechanical drive system, which is able to perform a fine course of angular motion, are reported. The system consists of a lead screw, a drive nut, sine bar legs, and an output shaft that can scan the optical holder mount. With a stepper motor coupled to the lead screw and interfaced to a PC, it is possible to control the scanning operation. When a 800 step/turn motor is used, it is possible to have an angular resolution of about 0.5 mdegree for a dynamic range of about 23°. The reproducibility of the results is about 0.22% for the scan angle and the hysteresis effect of the system is in the range of 1.71%. For a total scan of 51,200 steps, a scan angle of about 23.3° is acheived. The fitted line to the experimental results shows that scan angle changes linearly with the scan length. With good precision in system construction and careful alignment, the overall nonlinearity can be less than 1%.

Keywords: Drive system; Stepper motor; Optical element

1. Introduction

In many applications there is a need for a translation system that is capable of carrying or moving an object. Depending on the dynamic range of such devices they are classified as macro- and micro-scale systems [1]. Electromechanical devices are used for the macro-scale displacements, while piezo-electric actuators are utilized for the small-scale displacements [2]. Actuators are developed for small displacements with high resolutions. Therefore, motion accumulation has been developed for long-range traveling actuators. Such motion accumulation is based on racking, internal drive, walking, crawling, hopping, or multiple equilibrium positions [3]. The design and performance of an inchworm device is a typical example of the long actuation operation [4].

For many years conventional sine bar drives have been used in optical instruments that require scanning of the incident angle. Typical applications of such drive systems can be in the construction of equipment that requires scanning of an optical element like a mirror, polygon, or diffraction grating. A mechanical drive was reported in [5], which was based on a hinged sign bar drive that gives a true linear relationship even for large scanning angles. Theoretical and experimental investigation of a computer controlled angle tuning system was given in [6].

In this work, the previous design was modified in order to improve the resolution of the mechanical drive and, as a result, that of scanning system. The overall resolution and operation of the reported system depend greatly on the resolution of the lead screw, the stepper motor, and the drive module. Equally important to the system is the motor drive unit, which should be sufficiently smooth and precise to enable the full potential of the mechanical parts to be realized. Thus, a higher-resolution stepper motor was selected for the design, which offers a high constant torque over a wide speed range with low resonance and a good magnetic damping to minimize the overshot. To control the motor driver, an electronic module was devised, which provides full control of the stepper motor stage, including its speed and traveling condition. A new control method is also developed in this experiment, which takes advantage of MATLAB software [7].

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The novelty of the presented system is two-fold. Firstly, the proposed electromechanical drive system, in spite of simplicity, provides a high angular resolution and, secondly, the reported system is operated with a simple controller program on a PC. These two advantages make the reported device superior to available conventional drive systems [8].

2. Design and operation

Common drive systems for linear and rotary positioning mechanisms use the leadscrew, ball screw, and worm devices [8]. Leadscrew and riding nut is a very popular technique for moving loads. The axial translation of a nut riding a screw is used for linear poisoning. Such a device has advantages including self-locking capability, low cost, ease of manufacture and a wide choice of materials. Ball screw drives are actually leadscrews with a train of ball bearings riding between the screw and nut in a recirculating track. This device has a rounded shape to confine the recirculating balls. The primary advantages of ball screw over leadscrew may be higher efficiency, predictable service life, and lower wear rate. However, because it cannot self-lock, it requires an auxiliary brake to prevent back driving. The worm gear system is a technique of transforming rotary motion in one direction into rotary motion in another direction by meshing a screw with a gear. The advantages of worm drives over direct drives are higher velocity ratios and higher load capacities.

Fig. 1 shows the general arrangement for the reported mechanical drive system. The idealized geometrical diagram for the designed sine bar drive system is presented in Fig. 1(a). It has a fixed point at A, a hinge at B, and a movable pivot point at C. The lengths AB and BC of the triangle ABC ought to be equal, and the optical element normal is parallel to AB as shown in Fig. 1(a). For the case of AB = BC = b and AC = X, we can write

$$\sin\theta = \frac{X}{2b}, \tag{1}$$

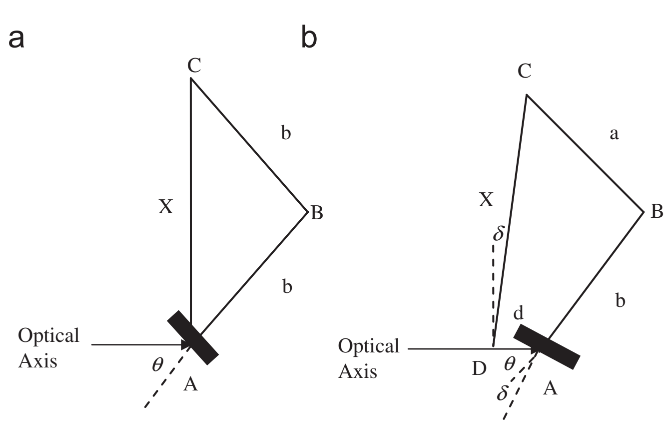

Fig. 1. Arrangement for the drive system. (a) Ideal geometry and (b) a more real case.

where θ is the optical axis angle. Each side of the triangle $b = 50$ mm and X can be varied from 50 to 100 mm. The output shaft of the drive provides a fine rotational movement. From Eq. (1) the theoretical range of the drive is found to be about 60°. The reported drive ensures a high tracking accuracy over a dynamic range of about 50 mm. By using two adjustable screws on the drive nut, the dynamic range of the unit can be adjusted for a smaller range. To define the range, two mechanical electro-switches are used, which disconnect the drive pulse upon touching the screws mounted on the drive nut. The linear distance between these two switches limits the operational range of the drive system. More details about the materials, parts, and construction design of the mechanical drive system can be found in the previous reports [5,6].

A more realistic arrangement of the triangle drive is shown in Fig. 1(b), in which the errors in construction and alignment processes are also considered. Errors can be introduced by a difference between the lengths AB and BC, due to the fact that the optical element normal is then no longer parallel to AB (angle δ in Fig. 1b), and that AC is not normal to the optical axis (angle δ in Fig. 1b). Furthermore, there is a possibility that the rotation point A and intersection of the optical axis with the line CD defining X do not coincide (distance d in Fig. 1b). The complete relationship without approximation is [6]

$$\sin\theta = \frac{X\cos\delta}{2b} + \frac{x(b^2-a^2)\cos\delta}{2br^2} + \frac{d - X\sin\delta}{r}\left[1 - \left(\frac{b^2-a^2+r^2}{2br}\right)^2\right]^{1/2}, \tag{2}$$

where $r^2 = a^2 + b^2 - 2Xd\sin\delta$. For a small value of δ, the first term in Eq. (2) is linear in X, but the remaining terms are not. The effects of the two nonlinear terms are calculated for this study.

Stepper motors are special motors that are used when motion and position have to be precisely controlled. A high-performance five-phase stepper motor, 800 step/turn (Sanyo Denki, 103-7550-140), is used in this experiment. A homemade electronic module was used for switching, which provides full control of the stepper motor. The electronic stepper motor driver is designed so that it can be operated with the PC by using the MATLAB software. The motor advances stepwise when a suitable input sequence pulse is applied. More details about the electronic module can be found in other references [9–13].

The primary concern in all the drive systems is the coupling of the motor shaft to the leadscrew. Direct flexible coupling is generally used in a drive system to transmit power and motion between two independent shafts, which may not be perfectly aligned. Depending on the applications, helical coupling and bellows are used for such a coupling. Bellows are generally used for low-duty usage, while helical coupling offers a smooth operation for high-speed applications. In addition to the mentioned systems, gearboxes are mainly used in reduction to produce increased resolution that may not be possible with standard motors. In addition to changing resolution, gearboxes with no-unity gear ratios also change the available output speed and torque. In our driver system a flexible coupling is used, but for a more precise application a better heavy-duty coupler is recommended.

A measurement set-up in general includes a mechanical drive, stepper motor, stepper driver,0 and controller, and a PC for running the control programs, as shown in Fig. 2. In the design shown in Fig. 2, the output from a He–Ne laser incident on a plane mirror is reflected and the laser image is marked on an image plane at a distance of about 2.9 m from the scanning mirror. By using trigonometry relationships, knowledge of the normal distance (2.9 m), and a record of the linear scan distance, the corresponding scan angle is determined with a good accuracy.

3. Results

Based on Eqs. (1) and (2), nonlinear effects are calculated using a MATLAB program and the results are shown in Fig. 3. The computed nonlinear term of the drive system is shown as a function of the scan length X for different values of error parameters δ (5 and 10 mrad). Our calculations indicate that the first nonlinear term in Eq. (2) does not have a significant contribution for this range of δ values, while the second nonlinear term dominates. For an assumed δ value equal to 5 mrad, the nonlinear error term contribution is about 0.5% for the maximum scanning length of 100 mm, and for a value of 10 mrad is about 1%. It is also noted that the nonlinearity effect is increased by increasing the δ value, as can be seen in Fig. 3.

In another study, the error source due to the triangle length, b–a difference denoted as ε, was investigated and the results are shown in Fig. 4. Variation of this nonlinear term as a function of the scanning length is shown for a range of 50–100 mm. The curves shown in Fig. 4 correspond to ε equal to 5 and 200 μm, respectively. The computed results indicate that the nonlinearity introduced by this term has the opposite effect compared with that of the δ parameter. For example, for $\varepsilon = 200\,\mu m$, the maximum effect at scanning length of 100 mm is about 0.07%, while for 5 μm is increased to about 0.46%. The result of this study indicates that this nonlinear term has a higher value at small-scan lengths, in comparison with its value for long scan ranges. As can be seen from this computation with a good construction and careful alignment, the total non-linear effect is calculated to be less than 1%.

To test the operation of the reported system for the angle scanning, a simple control program is written in MATLAB. In the first investigation, the linear deflection of the incident laser light is measured and the experimental results are shown in Fig. 5. The tracking accuracy can be measured in terms of the number of scan steps. However, for some applications, direct measurement is recommended. The linear scanning distance measured on the image plane is shown in Fig. 5 for 51,200 steps of the stepping motor. With the present systems two mechanical micro-switches are used for the stop function of the stepper

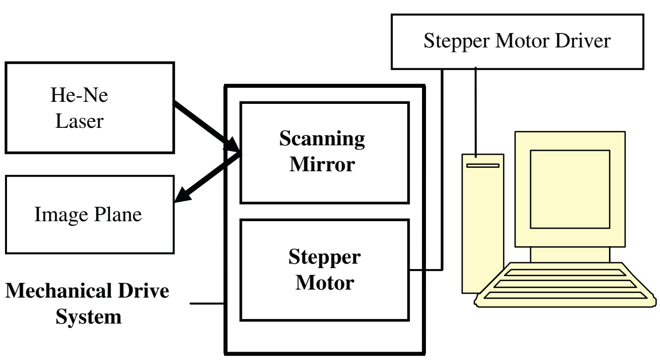

Fig. 2. Experimental set up for the operation of the scanning system.

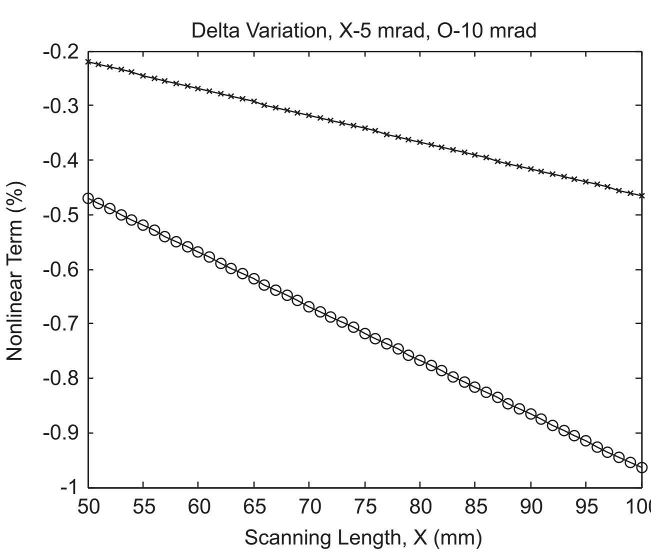

Fig. 3. The computed nonlinear effect of the drive system for parameter δ.

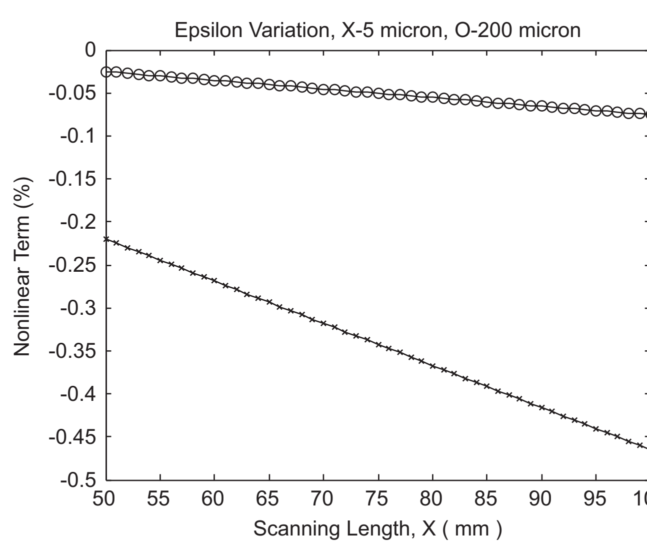

Fig. 4. The computed nonlinear effect of the drive system for b–a.

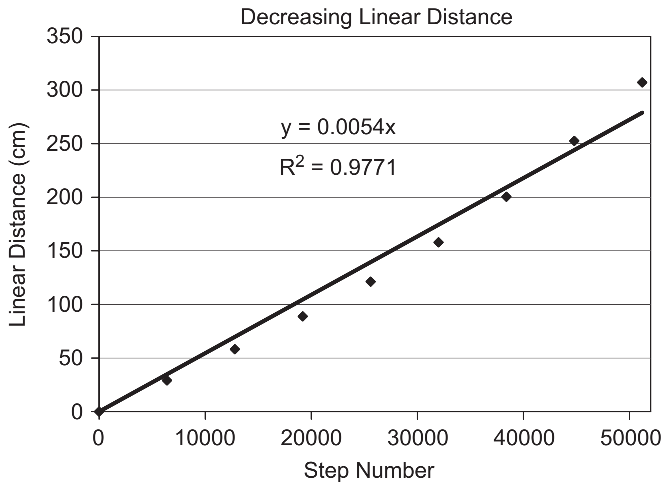

Fig. 5. Variation of linear distance as a function of step numbers.

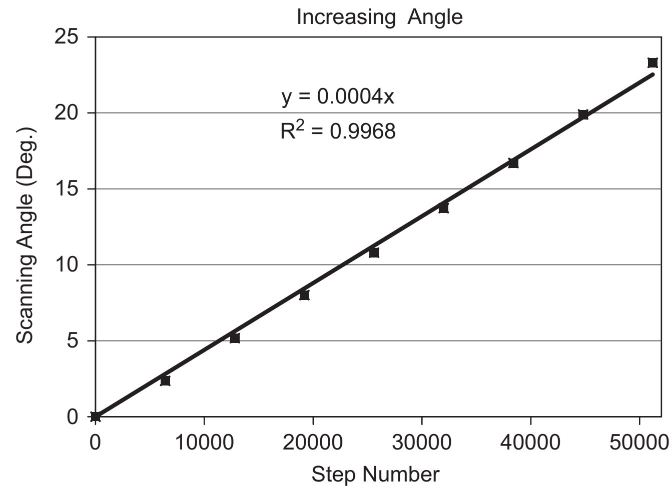

Fig. 6. Angular scans as a function of the step numbers.

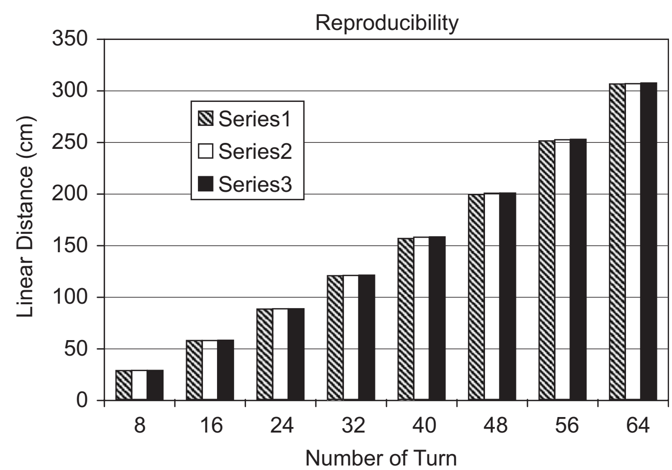

Fig. 7. Reproducibility of the results for the designed scanner.

motor and the drive nut. For one turn operation of the device an opto-coupler assembly connected to the motor shaft is also devised. In terms of the on/off functioning, the accuracy of the opto-coupler is higher than the electro-mechanical switches and offers precise zero positioning of the drive in short scans.

The data points in Fig. 5 show the measured values, while the trend line is a least-squares fit. The gradient is 0.0054 cm/step with a correlation factor, R^2, of 0.977. As can be seen in Fig. 5, the variation of deflected beam distance is linear with the number of the scanned steps. For a total of 51,200 steps, the deflection on the image plane is 307.10 cm. This is for the case of decreasing distance and for the reverse case the linear light deflection is 307.76 cm. The linear resolution of the present system obtained from Fig. 5 is 54 μm/step or 4.32 cm per motor turn.

The trigonometric relationship is used to determine the scanning angle. The results for the case of increasing scan angle are shown in Fig. 6. For a total of 51,200 steps, the scanned angle change is 23.3°. The gradient is about 0.0004°/step (0.4 mdegree/step) with a correlation factor, R^2, of 0.9968. The angular resolution of the present system obtained is 0.4 mdegree/step, which corresponds to 0.32°/turn for the present scanning drive mechanism. It must be noted that the angular resolution of the step motor is only 0.45°/step (800 step/turn).

Precision is defined as a measure of the reproducibility of the measurements, and is considered as a figure of merit for such a scanning device. Such a parameter indicates the ability of the device to reproduce output results when the same drive pulse is applied to it subsequently under the same condition. Fig. 7 shows the repeatability of the reported system for three consecutive runs. The reproducibilities of the measured linear distance for the three different runs are recorded and the results are compared in Fig. 7. The maximum difference for the two different runs is about 1.2 cm for the full range of the scan, which corresponds to 307.10 cm and to 64 turns of the stepper motor. This leads to a reproducibility of 0.3% of the full-scale range. For a better comparison, the average value for three different scans is calculated and the result is used as the calibration line for the designed system.

In Fig. 8, the reproducibility of the results in terms of the scanning angle is presented. The vertical graph bars show such a difference in mdegree for two different scanning tests. As can be seen in Fig. 8, the minimum difference is about 9.75 mdegree and the maximum deviation is about 93.5 mdegree. The average value for the angle difference is about 51 mdegree, which represents good reproducibility. In terms of the scanning angle, this corresponds to a reproducibility of 0.22% for the full-scale range of 23°.

Such repeatability measurements are also performed for the case of reverse scanning direction, which gives a similar result. The stability of a system is another important parameter, which is also investigated in this study. In general, such a factor shows the ability of the device to maintain its performance characteristics for a certain period of time and the reported system shows a very good stability with time. Since the electronic drive module works with high-power transistors, to prevent heat effects on the

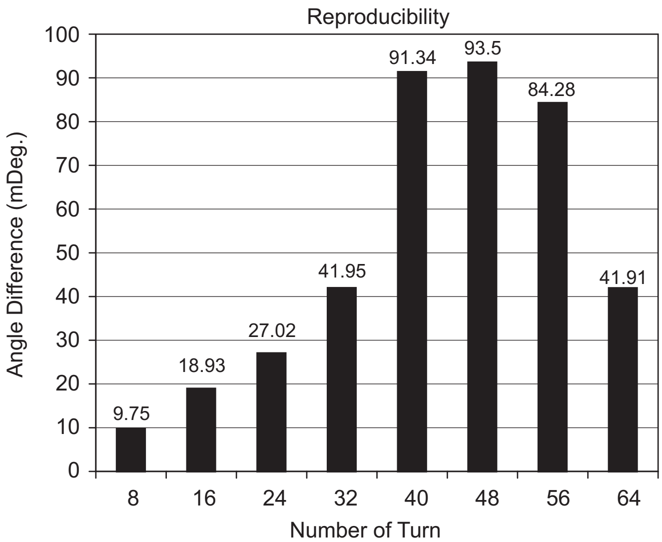

Fig. 8. Reproducibility in terms of scanning angle difference.

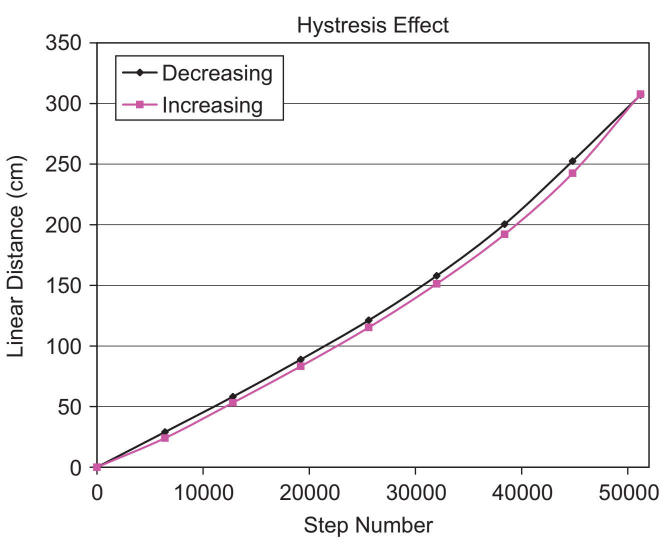

Fig. 9. Hystresis effect of the designed scanner.

drive pulse, a cooling fan was used for the module in order to maintain a constant temperature of about 20 °C during the operation. Application of light oil to the lead screw and drive nut provided a smooth course of operation for the mechanical drive during the scanning range of about 40 mm.

In all scanning systems it is important to have the minimum hysteresis when scanning is performed in opposite directions. Such effect for the reported system is presented in Fig. 9 when testing the scanning drive system for the case of decreasing and increasing distances. As can be seen in Fig. 9, for two opposite directions there is little difference between the results and most of the data points are matched very well. However, the minimum deviation is 0.56 cm while the maximum deviation in two related scan points is about 10 cm. The average hysteresis error for the system is 1.71% of the full range. Part of the measured differences is due to the irregular on/off operation of the two micro-switches as described before and also due to the coupler condition used to connect the motor shaft to the lead screw of the drive system.

Comparison of the performances of the drive system for small and large angles can be made from Fig. 10a, b. Because scanning at lower speed takes place some times, the results are obtained for a limited scan angle of 11.658°. For the small angle the linear agreement is almost perfect. The fitted line shows a correlation factor of 1 with respect to the measurement data points as shown in Fig. 10(a). On the other hand, for the larger angle of about 23.3°, Fig. 10(b), the linear relations still hold well with a good correlation factor of about 0.9995. This comparison shows that the reported system can be used for scanning of the larger angles with a high resolution and repeatability of the results.

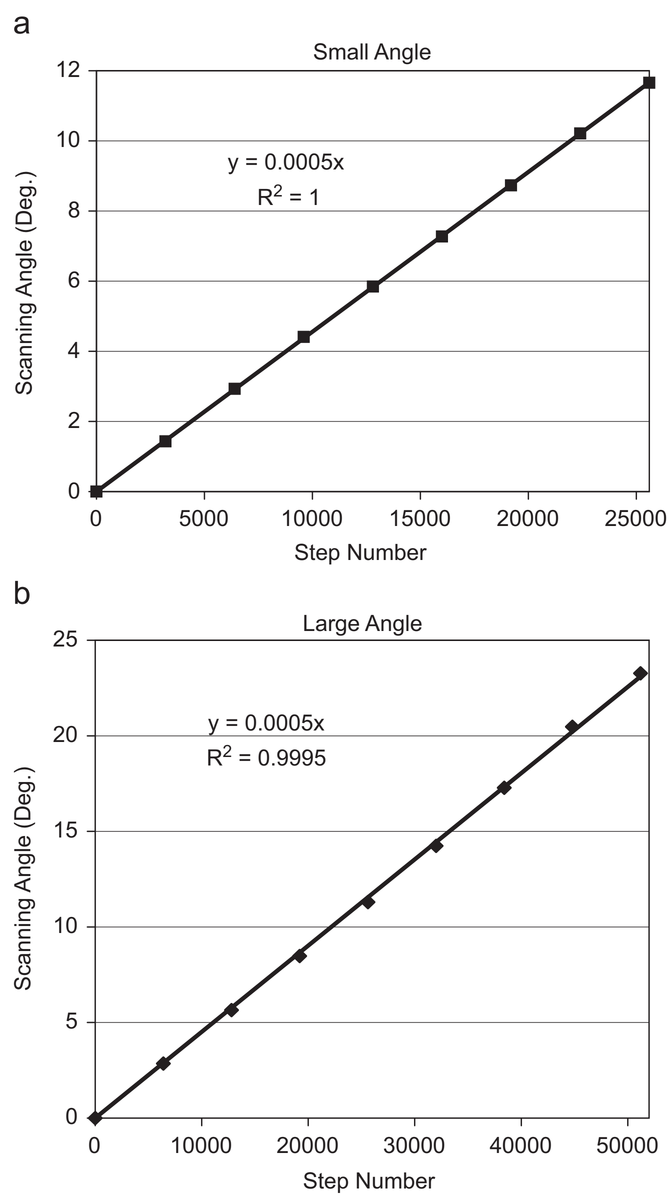

Fig. 10. Comparison of the system performance for the small angle (a) and large angle (b).

4. Conclusion

When a 800 step/turn motor is used, it is possible to obtain an angular resolution of about 0.5 mdegree for a dynamic range of about 23°. Precision rotation stages are commercially available with properties that are ideal for fine-tuning angular orientation of any component [8]. In such designs, the bearings are preloaded into precision-ground steel rakes for a smooth, accurate trajectory with minimum eccentricity. The clutch knob permits a continuous rotation of the stage over a 4° fine motion and a 360° coarse motion with a minimum vernier graduation of 1° or 1 arcmin. This stage provides a sensitivity of about 2 arcsec. The direct scanning of an optical element with such a rotation stage provides a resolution of 1°. Using a similar stepper motor (800 step/turn) to drive this stage, the resolution of such a system can be improved to 1.25 mdegree/step. However, our reported system provides a higher resolution of (0.5 mdegree/step) that is better than the best conventional stepper-motor-driven rotation stage.

With a simple modification of the drive system it is also possible to use the half-step excitation drive option in order to improve this resolution by a factor of 2. Based on our theoretical and experimental results the reported folded sine bar scanning system provides high resolution, and high linearity, even for larger scanning angles if the proper care is taken into consideration in its construction. The reported system is ideally suited for optical instruments such as, grating drives of the monochromator [14], spectrophotometers, laser scanners [15] and tunable dye laser systems in which scanning operation is required.

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