Long Range and High Axial Load Capacity Nanopositioner using Single Piezoelectric Actuator and Translating Supports

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Existing long range piezoelectric motors with friction based transmission mechanisms are limited by the axial load capacity. To overcome this problem, a new linear piezoelectric motor using one piezoelectric actuator combined with a novel stepping mechanism is reported in this paper. To obtain both long range and fine accuracy, dual positioning control strategy consisting of coarse positioning and fine positioning is used. Coarse positioning is used for long travel range by accumulating motion steps obtained by piezoelectric actuator. This is followed by fine positioning where required accuracy is obtained by fine motion displacement of piezoelectric actuator. This prototype is able to provide resolution of 20 nanometers and withstand a maximum axial load of 300N. At maximum load condition, the positioner can move forward to a travel distance of 5mm at a maximum speed of 0.4 mm/sec. This design of nanopositioner can be used in applications for ultra precision positioning and grinding operations where high axial force capacity is required.

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NOMENCLATURE

K_1 = Stiffness of input shaft
K_2 = Stiffness of output shaft
P = Axial load acting on the output shaft
B_1 = Backlash at the input feeding screw
B_2 = Backlash at the output feeding screw
Δx = Increment in actuator length
U = Anticlockwise angular motion in backward motion
L = Amplitude of drive signal
Y = Position variable
Y_i = Fine positioning variable
Y_t = Threshold position of the actuator
Y_g = Target Position of the actuator
N = Number of drive steps

1. Introduction

Actuation with a nanometer positional resolution is necessary for a wide range of applications like microscopy, ultra-precision machining, micro assembly, data storage, etc[1]. Designs which provide nanometer level positional resolutions are summarized in table 1. They are classified according to axial load capacity. Each of these designs has their own advantages and disadvantages. Piezoelectric actuators are based on the special property of Lead Zirconate Titanate (PZT) material which expands when a positive voltage is applied along their length. Magnetostrictive materials expand in the presence of magnetic field. Both piezoelectric actuators and magnetostrictive actuators can actuate against high axial force, but are limited by achievable travel range. Linear piezomotors are structures which have one or more piezoelectric actuator integrated in the structure. Designs based on this concept are inchworm actuator, ultrasonic motor and stick-slip actuator. Inchworm actuator[2,3] uses three piezoelectric tubes. Two of them are used to clamp in radial direction and one of them to expand and contract longitudinally. When three drive voltages are applied on these three tubes with a certain phase difference, one of the outer tubes grips the shaft and the other tube expand or contract creating a motion displacement. In an impact force piezomotor[4], the system is composed of three units: a body, a piezoelectric actuator and a mass. The actuator links the mass and body. When the driving voltage of the piezoelectric element is increased slowly, the piezoelectric element expands and the mass moves to the right. This is followed by a quick decrease in the voltage. During this quick shrinking, the inertial force of the mass to retain the original position exceeds the maximum static frictional force of the body. Consequently, by repeating this cycle the body moves step by step. Stick-slip actuators[5] are other class of piezomotors which consist of two piezoelectric legs supporting a body load. These legs are deformed either abruptly or slowly at a constant rate. To create a motion displacement, a slow deformation is first applied and then an abrupt backward deformation is applied. Due to inertia of the whole body, the body does not move backward when abrupt backward deformation takes place. Ultrasonic actuators move the body due the vibration created by a set of piezoelectric actuators[6,7,8]. One simple configuration[6] uses four piezoelectric actuators making both longitudinal and bending oscillations creating an elliptical oscillation.

Table 1 Summary of previous designs

Load capacity	Positioning Device	Resolution (nm)	Travel Range	Reference
Low	Inch Worm	4	Long	2
	Ultrasonic Motors	160	Long	6
	Impact Force Piezomotor	100	Long	4
	Stick-Slip actuators	5	Long	5
High	Single Piezo actuator	1	Short	15
	Hydraulic Actuator	1	Medium	9
	High Stiffness Actuator	5	Long	13
	Active Lead Screw	10	Long	10
	Dual Positioning	1	Long	14

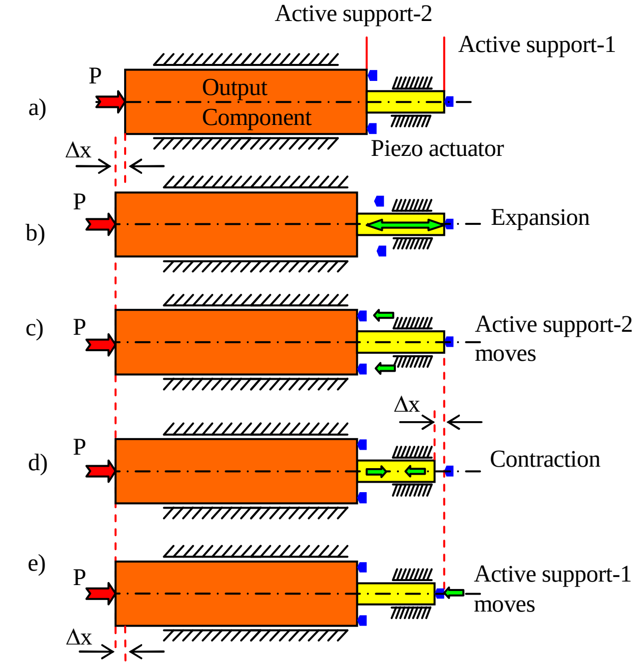

Fig. 1 Mechanism of the actuator

This elliptical oscillation is transferred to the body which results in a motion step.

It should be noted that these designs are based on the frictional forces to withstand any axial input force. This makes them suitable only for applications which need long travel but not for high axial force applications. Applications like feed drives for ultra precision machining and grinding need to meet three positioning requirements: 1) Withstand high axial load 2) Resolution in the order of tens of nanometers and 3) Long travel range. Hydraulic actuators[9] using differential pressure operation can achieve nanometer resolution and also withstand high axial loads. But they are limited by their complex design and contamination issues. Active lead screw mechanism[10] uses piezoelectric actuators to compensate backlash in traditional lead screws. They can with-stand high axial loads and also provide long travel range. But their design and control methods are complicated and moreover stick-slip effect has been a concern for these designs. Dual positioning[11] using both hydraulic cylinder/linear motor and piezoelectric actuator have been reported to achieve a positional resolution of 5 nm and also provide high axial load capacity. These positioning systems need special attention for controlling the interference of one positioning entity on other. Fakuda *et al.*[12] demonstrated nanometric positioning over one mm stroke using flexure guide and electromagnetic linear motor. Zhu[13] reported a design of high stiffness linear motor integrated into the machine tool guide way. The design consisted of a monolithic flexure and three piezoelectric actuators. Two piezoelectric actuators actuate as clamps and one piezoelectric actuator is used to move the system forward. Six individual steps have to be made to get the required travel. Clamping was achieved by the opposing frictional force between the guide way and part of the flexure. This method requires three piezoelectric actuators with three individual control inputs.

Ngoi *et al.*[14] has reported a nanopositioner design based on self-lock mechanism to withstand high axial forces. This design uses a structure consisting of a single piezoelectric actuator and moving slopes as supports. This design even though feasible cannot be automated and controlled for high speed applications. The designs

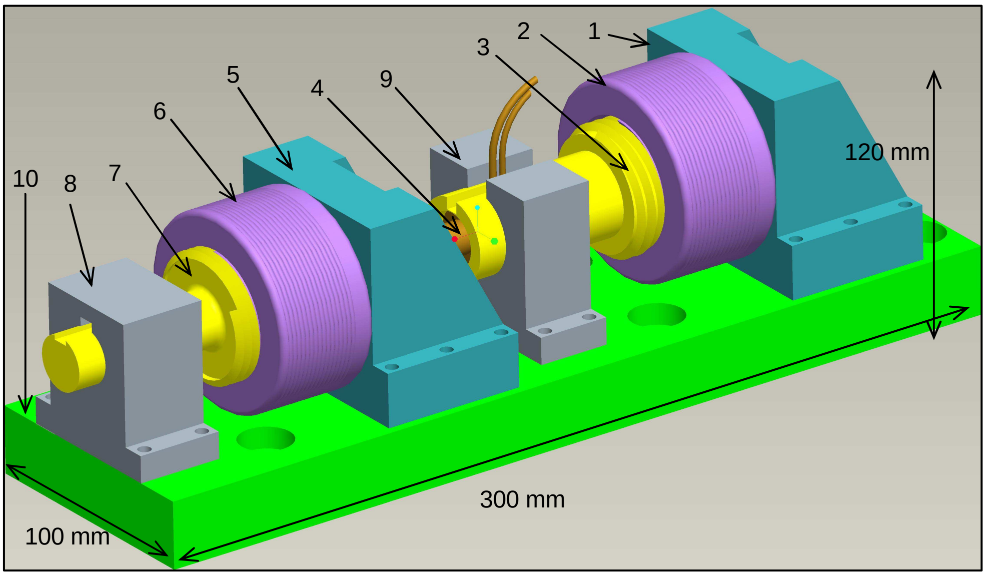

Fig. 2 Geometric model of Nanopositioner (Base (10), Supports (1, 5, 8, 9), Feeding screws (6, 2), Input and Output Shaft (7, 3), Actuator assembly (4)). Stepper motor assembly connecting the feeding screws is not shown in the figure

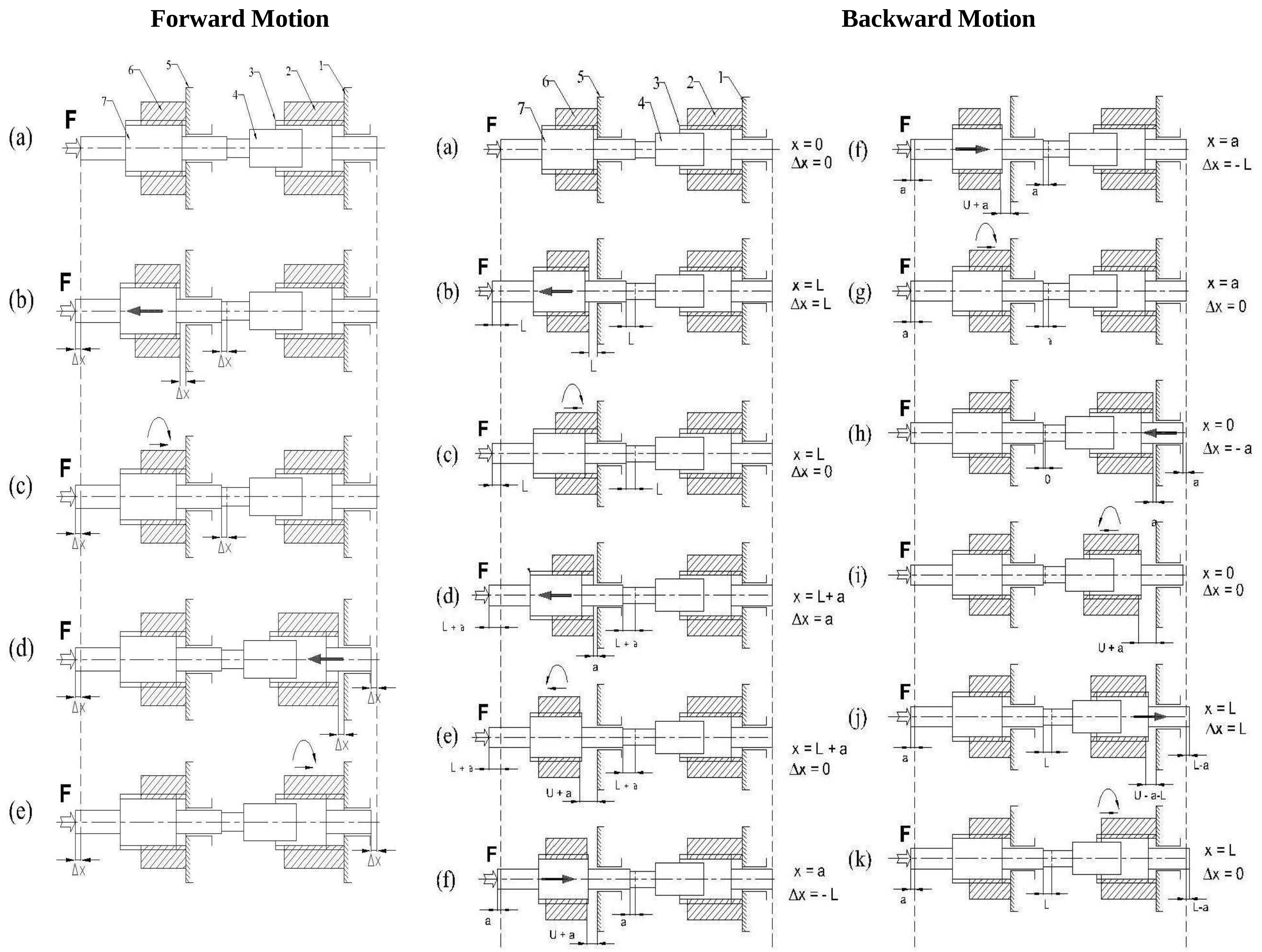

Fig. 3 Operation of forward motion and Backward Motion (Input support(1), Input feeding screw(2), Input shaft (3), Piezoelectric actuator (4), Output support (5), Output feeding screw (6), Output shaft (7)). In backward motion schematic, x represents the extension of actuator and Δx represents the increment in the extension

mentioned above either cannot withstand high force or they are limited by travel range. Designs that can achieve these requirements are limited by complex design or sophisticated control methods. To achieve high axial force capacity, long travel range, high speed and easier control, we propose a screw based nanopositioner using one piezoelectric actuator. The paper is divided into three sections. First section describes the principle, forward operation, and backward operation and displacement losses. Second section contains the details on prototype model, control strategy and experimental setup. Finally performance results, discussion and conclusion are presented.

2. Design of the Nanopositioner

2.1 Principle of the design

Using a single piezoelectric actuator and two active supports, we report the design of a single axis nanopositioner which can withstand large axial load and provide a long travel range. The mechanism of this design is shown in fig. 1 and described as follows:

1. Both piezoelectric actuator and the output component (component on which load acts) lie on the same axial line as that of the motion direction.
2. Active supports are used to support the input axial load during the time when piezoelectric actuator is inactive. Thus they are expected to produce a necessary reaction force against the input axial force whenever required.
3. The required travel range is covered in two stages a) Coarse positioning stage and b) Fine positioning stage. In the coarse positioning, piezoelectric actuator covers most of the target travel displacement by accumulating small displacement steps. In the later stage, the same piezoelectric actuator is used to achieve motion with nanometer accuracy by simple extension.
4. In order to accumulate the motion steps (consecutive expansion and contraction) into a macroscopic displacement for both forward and backward operation, accumulating mechanisms using moving active supports are used.

2.2 Forward and backward operation

Using this mechanism of moving supports and successive expansion and contraction of piezo electric actuator, we have designed a positioning system as shown in fig. 2. The system consists of input and output feeding screws (2 and 6), input and output shafts (3 and 7), input and output supports (1 and 5) and a piezoelectric actuator (4). The internal threads of feeding screws are engaged with external threads of shafts such that the faces of the feeding screws touch their respective supports. The two shafts are allowed to slide through the supports interconnected with a piezoelectric actuator in between. Stepper motors are used to provide torque to feeding screws for the forward and backward operation of the positioner. Forward motion of the positioner is obtained by motion steps achieved by successive expansion and contraction of piezoelectric actuator as shown in left side of fig. 3. At the start of forward operation of the positioner, the axial load P is totally supported by input support (1) and self-lock effect between input feeding screw (2) and input shaft (3). To start the operation of the positioner, piezoelectric actuator is expanded by an amount of Δx to create a clearance between output feeding screw (6) and output support (5). This clearance is filled by imparting a clockwise torque to the feeding screw (6). After filling the gap, piezoelectric actuator is contracted to create a gap between input feeding screw (2) and input support (1). As soon as the contraction starts, the whole load is now supported by output support (5) and self-lock effect between output feeding screw (6) and output shaft (7). The final step includes clearing the gap formed between input feeding screw (2) and input support (1). Continuing the above steps, the piezoelectric actuator is able to move the load P ahead by a displacement step equal to Δx. The clearance gaps in the operation of the positioner can be filled by applying a clockwise torque to the feeding screws. The torque is carefully chosen only to fill the gap and not to displace the shafts forward.

Backward operation is possible only with actuator's pre-extension and feeding screws touching their respective supports. Backward motion is obtained in seven sub-steps as shown in right side of fig. 3. The operation begins with an extension of *a*, which creates a gap of *a* between the output feeding screw (6) and output support (5). This gap is increased by imparting an anticlockwise torque to *U+a*. Next the piezoelectric actuator is contracted by *L* and the gap between feeding screw (6) and the support (5) is filled by providing a clockwise torque to feeding screw (6) such that its face touches the support. By this time, the load moves *L-a* backward and is supported completely by the feeding screw (6). The next step involves a contraction of *a*, which creates a gap of *a* between input feeding screw (2) and input support (1). This gap is further increased to *U+a* by imparting an anticlockwise torque to the feeding screw (2). This is followed by an expansion of L and filling the gap between feeding screw (2) and support (1) by providing a clockwise torque to feeding screw (2). After following the above seven sub steps, the system returns to initial state of pre extension of L and completes one backward step of *L-a*. Backward motion of desired displacement is obtained by repeating these steps. Deflection of the structure when subjected to such axial forces can cause a loss in the output displacement. Ideally when axial force is small, the output motion step of the positioner will be equal to the input elongation of the piezoelectric actuator. But as the magnitude of the applied axial force increases there is displacement loss due to the deflection in the direction opposite to the motion. The sources of loss are deflection of the feeding screws, feeding supports and the piezoelectric actuator, which form a mechanical assembly.

Elastic deformation of the piezoelectric actuator is small compared to the feeding screws as the stiffness of the piezoelectric is relatively high. During the expansion stage the feeding screw takes the total load and the output displacement is less by the deflection happening both at the input screw - support interface and at screw joint. During contraction the whole load is taken by output feeding screw-support interface and output feeding screw joint. Therefore the displacement loss in one cycle of extension and contraction is equal to summation of these deflections. If the load acting upon the positioner is P and the extension of L is applied then the loss is $P/K_1 + P/K_2$ where K_1 and K_2 are the overall stiffness of support and screw joint at input and output side respectively. In addition to deflection loss, other loss occurs due to backlash, this loss occurs due to the load acting on the screw causing them to move backward during forward operation. In the operation of forward motion, backlash loss occurs at input feeding screw during the expansion process and occurs at output feeding screw during the contraction. So the total loss is given as $B_1+B_2+P/K_1+P/K_2$ where B_1 and B_2 are the backlash losses and P/K_1 and P/K_2 are the deformation losses. Fig. 4 shows the occurrence of these losses during one displacement step where the piezoelectric actuator expands and contract slowly at a constant rate. Dual positioning with both coarse and fine positioning is used as control strategy for this research. Fig. 5 shows the detailed algorithm of dual positioning. In coarse positioning, step motions by piezoelectric actuator are used to accumulate to a threshold value generally 2-3 μm lesser than the actual target. Due to the losses in displacement during

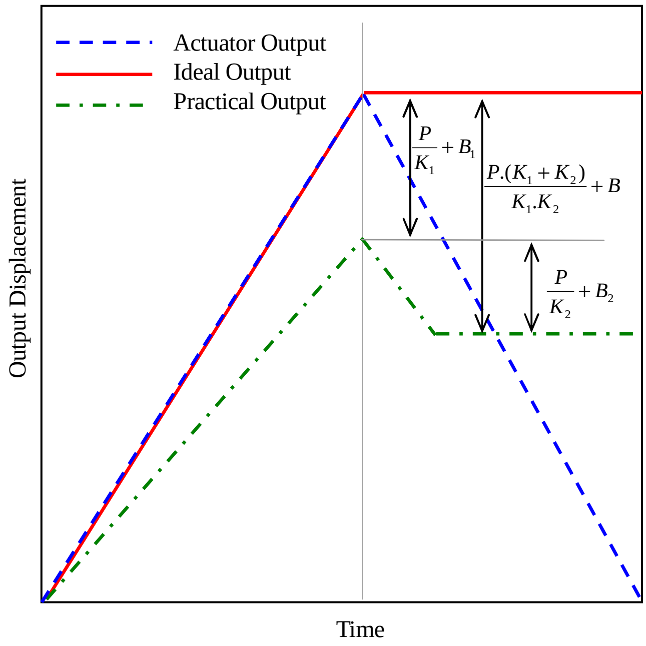

Fig. 4 Ideal output , actuator output and practical output in one step motion

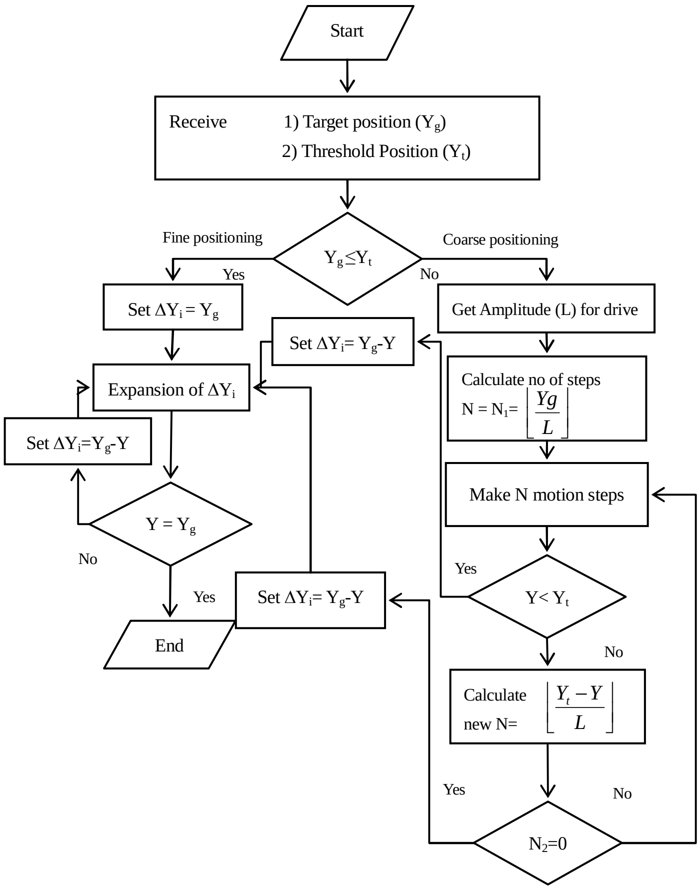

Fig. 5 Algorithm used for dual positioning (Y is the position variable)

single step motion, the actual number of steps are calculated and accumulated on real-time basis to reach the threshold value. After the threshold is reached, fine positioning is done using closed-loop actuation of piezoelectric actuator. This ensures positioning with the piezoelectric actuator's nanometer level accuracy and precision. It should be noted that the effect of backlash and deflection losses on the output accuracy are eliminated by dual positioning strategy.

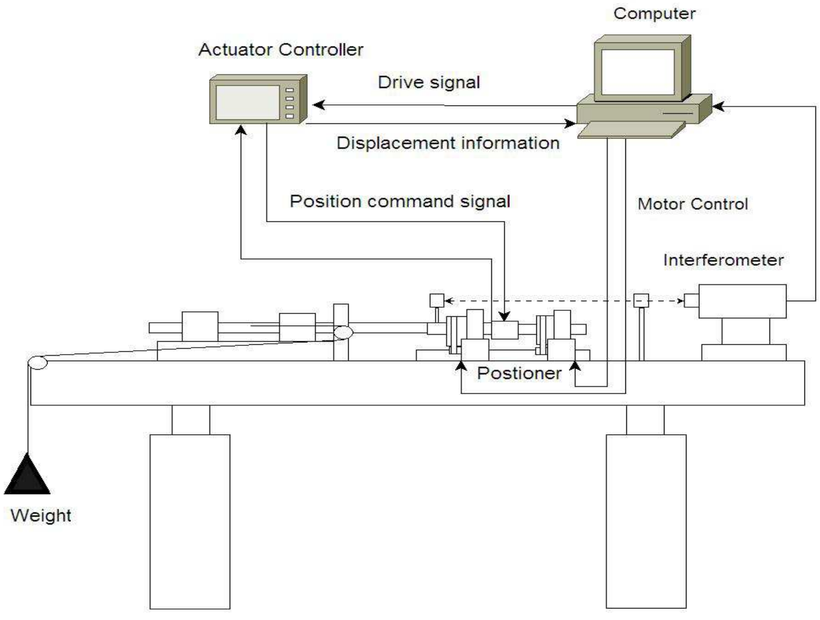

Fig. 6 Experimental setup of the nanopositioner

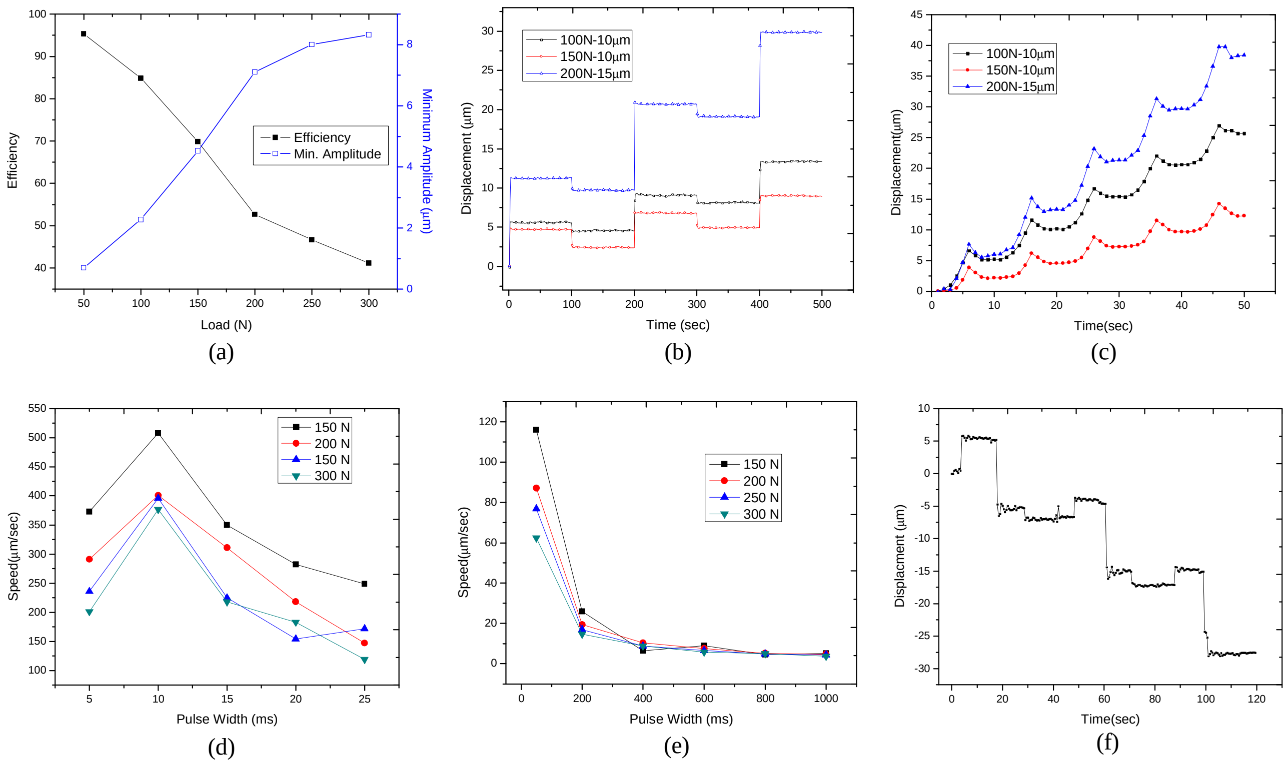

Fig. 7 Performance of nanopositoner a) efficiency and minimum displacement for the nanopositioner b) forward motion with a square signal c) forward motion with a triangle signal d) dynamic performance with short pulse width e) dynamic performance with long pulse width f) backward motion of the nanopositioner

3. Experimental

3.1 Measurement and Experimental setup

The experimental set-up is illustrated in fig. 6. The experimental setup consists of a computer, amplifier/controller, nanopositioner, an interferometer, stepper motor setup and load applying rig. A load applying setup was fabricated and installed such that a static predetermined load P can be applied on the nanopositioner. To apply a stable axial load P to the output bar of nanopositioner, two pulleys are used to convert the gravity of a suspended weight to form a push force P. The magnitude of the load P is equal to the gravitation force of the hung-weight. The load P was regulated by changing the hung-weight for different experiments. The piezoelectric actuator used in this research, is the product of Physik Instrument.[15] This stack-type actuator (Model no: P-845.10) whose diameter is 20mm and length of 63mm provides a resolution of 0.3 nm and can withstand a maximum force up to 3000N. It also has an inbuilt displacement sensor for closed loop position control purposes. The piezoelectric actuator can be controlled by either voltage or position. For this research, positional control is only used. An interferometer was chosen as a sensor due to its accuracy and non-contact long range data acquisition. Renishaw interferometer, which has a resolution of 0.001μm[16] was used as positional sensor to acquire the position information both for coarse and fine positioning operations. Position information obtained from this sensor is a box-car average of 256 reading taken for every 250 millisec. Two stepper motors (Japan Servo Ltd, Model No: KH56KM2) with a stepping angle of 1.8° were each cycle makes the actuator increase and decrease its length slowly by a constant rate. Square drive signal causes the actuator to extend and contract abruptly. Drive signal is characterized with its amplitude and pulse width. Pulse width of a signal is the duration of expansion and contraction. Static experiments with very long pulse width drive signals are shown in fig. 7(b) and 7(c). Different curves are obtained for different sets of load and amplitude. These performance characteristics show the displacement loss occurring due to backlash and deformation. The variation in the displacement at different loads

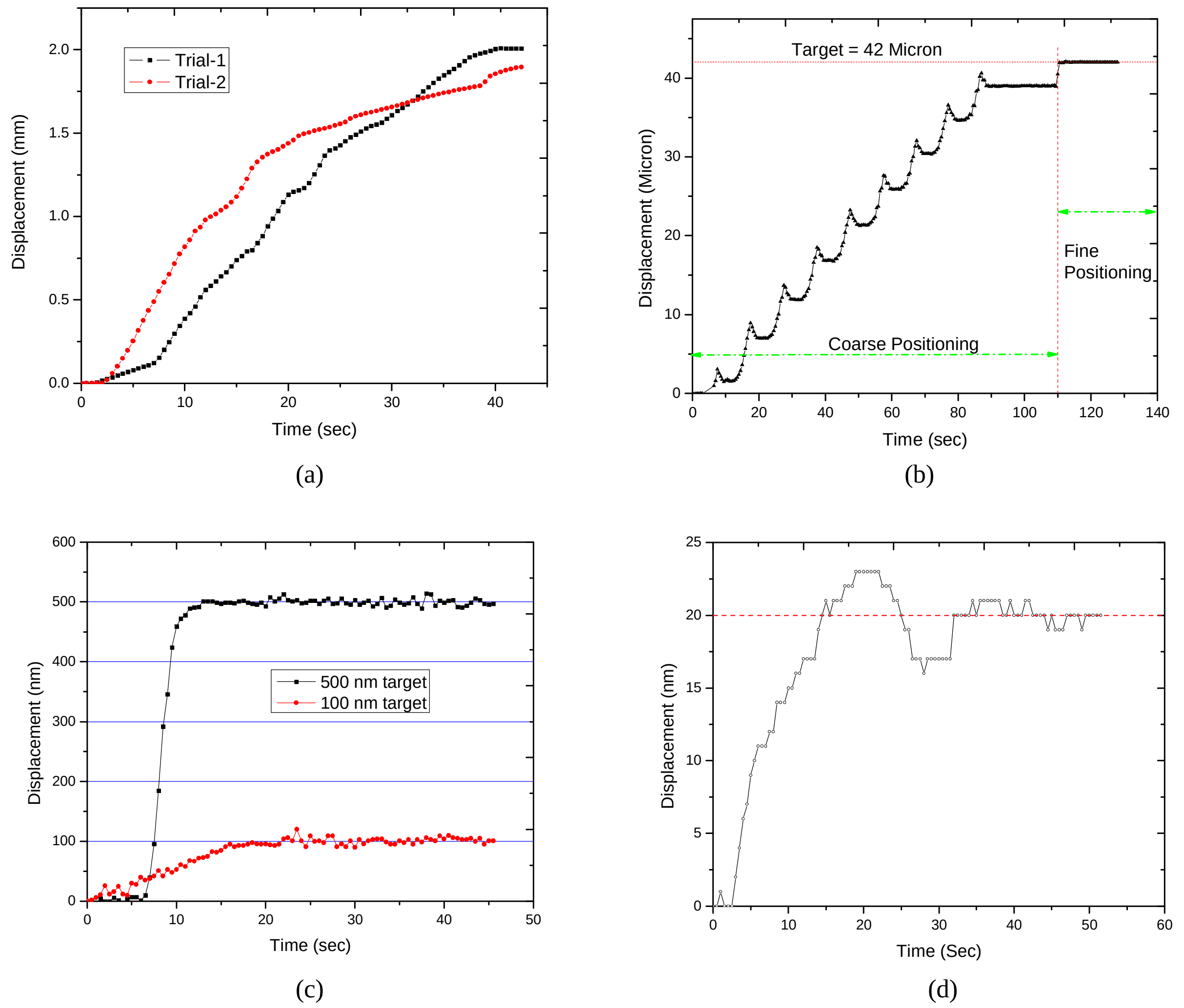

Fig. 8 Performance of nanopositoner a) Long range positioning b) Hybrid positioning c) Fine positioning d) Minimum resolution performance

installed beside the nanopositioner to provide driving torque. The torque is transmitted through driving belts to both input and output feeding screws. These two stepper motors were controlled by BASIC stamp module. All the components were installed on an optical bench with laminar flow vibration control activated. The whole setup was maintained at optimal humidity and pressure levels. The setup was also covered with polyfoam box with aluminum foils pasted on inner sides to avoid any acoustic disturbances. Data acquisition, automation and closed loop operations were accomplished using Labview7.0™ software from the computer in the setup. Piezoelectric actuator amplifier was controlled with GPIB communication and BASIC Stamp® module was controlled by RS-232 communication.

3.2 Performance and Discussion

Continuous forward motion is obtained by sending either a triangle or square shaped drive signal to piezoelectric actuator. A drive signal is a continuous series of cycles. In a triangle drive signal,

occurs due to the variation in deflection losses. Experiments were conducted to find the minimum amplitude required to operate for both forward and backward motion. Triangle drive signals with very long pulse width were used to calculate the static loss due to deformations. Efficiency of the positioner is defined as the ratio of the output displacement to input extension in one step displacement and is related to the axial load applied on the nanopositioner. Experimental results were obtained for a load ranging from 50 N to 300 N. Minimum displacement required at different loads and efficiency are plotted in fig. 7(a). It can be observed that efficiency decreases and the required minimum displacement increases as the applied axial force increases. Dynamic performance or performance with short pulse width drive signals at different loads is shown in fig. 7(d) and fig. 7(e). It is observed that speed of travel is dependent on drive signal pulse width and the acting axial force. It can be seen from fig. 7(e) that for the same number of cycles and for pulse widths larger than 50 ms, speed is nearly inversely proportional to pulse width. But when the pulse width is less than 50 ms, speed of the positioner decreases after reaching a certain limit the results as shown in fig. 7(d). This happens as the time needed to fill the gaps in between feeding screws and supports are longer than the expansion and contraction time. This results in loss of displacement and reduces the overall speed. It has been found that the optimal signal pulse width is almost the same for the whole load range. Fig. 7(f) shows the backward motion obtained at a load of 150 N with L = 10µm and a = 5µm. Backward motion tests were conducted with very long pulse width signals to simplify the operation. Fig. 8(a) shows a long range result. The test was conducted at 150 N force with a square signal of 15 µm amplitude and a 25 ms pulse width. The variation in two different runs may be due to the change in frictional force at the feeding screw and shaft engagement area. For larger displacements, hybrid positioning according to the algorithm stated in fig. 5 is used and a typical performance result for a target of 42 µm is shown in fig. 8(b). It can be noticed that when coarse positioning is completed after reaching a certain threshold position (38 µm in this case), fine positioning is used to get precise and accurate displacement. For output displacements smaller than 1000nm, only fine positioning can be used. Fig. 8(c) shows such experimental result for 500nm and 100nm target. It can be observed that the repeatability or precision is about 10nm and is predominantly dominated by electrical noise from the interferometer system. The minimum resolution of this nanopositioner is 20nm as shown in fig. 8(d). The variation of 1 nm in the resolution performance test may be due to the noise in the interferometer system. Experiments for obtaining resolution less than 20nm have been unsuccessful due to inconsistency in results. In summary, the current design of nanopositioner has a maximum load limit of 300 N at 40% efficiency, an accuracy of 10 nm, a resolution of 20 nm and maximum speed of 375 µm/sec for an input load of 300 N. The limitations of the current design and the control method used are the time to attain the required target position and the observed driving ripple. Improved and advanced control methods need to be implemented to overcome these limitations. Future work will be focused on these aspects and to obtain better backward motion results. These results will be reported somewhere else.

4. Conclusions

We have reported a novel linear piezoelectric motor which can withstand high axial load and provide long travel range. This novel motor is designed for traditional applications in precision engineering where both ultra precise motion control and high axial load capacity are essential. The reported nanopositioner uses accumulation of small displacement steps either in forward or backward direction to obtain long travel range. From performance results, it is observed that 1) efficiency of this design decreases with increasing axial force. 2) Maximum speed of travel is obtained from a drive signal with an optimal pulse width. Hybrid positioning control strategy using coarse and fine positioning is able to compensate both backlash and deflection losses providing the required travel displacement with essential accuracy. This design under a maximum load of 300N has achieved a travel range up to 5 mm.

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