An Approach to High Precision Positioning and Measurement by Integrating Modern Simulation Tools

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- INTRODUCTION:

Positioning systems are widely used in many industrial applications such as actuation, CNC machining, automatic testing, calibration, inspection, and processes such as laser welding or cutting . Micro positioning refers to mechanical movement with positioning accuracy and resolution in the micron or high sub-micron range. Nano positioning refers to positioning with nanometer or sub- nanometer resolution range for high – precision Nano positioning devices.

Applying design rules for motion systems with millimeter or sub- millimeter resolution do not always apply for the micron and sub-micron range.

Resolution in the sub- micron realm cannot always be increased by simple means such as reducing the pitch of a leads crew or increasing the gear ration of a motor/ gearhead unit. Station / friction, play, backlash, tilt, windup and, temperature effects, etc., will also limit accuracy and resolution Sub- micron positioning systems require a great deal of attention in design, manufacturing and selection of materials.

These applications require that the positioning system have high accuracy and good repeatability. As result, this project's purpose was to introduce various ways to measure the actuation of the stage. The proposed measurements are very cost effective to implement in many organizations. The implementation and measurement of positioning was accomplished using four simulation tools and related software. The visual simulation software was used along with the software, which provided an example of hardware- in- the loop. The experiments also included three methods of position measurement. Amongst the methods implemented, interferometry method was adjudged to be the best case.

- Overview of errors in measurement system:

- contribution of errors:

Total error is the cumulative effect of linear displacement error, angular error, and error due to straightness, parallelism, orthogonally, spindle thermal drift. Out of the above linear errors, displacement error is of prime importance in precision machine tools, for a sample linear stage in figure (2- 1)

- **Linear displacement Error**

Linear displacement error is defined as translation error movement of a machine component along its axis of movement in general, this type of error is caused by the geometric inaccuracies of the drive or encoder unit. The resolution of the encoder can result in this type of error , for example, if the resolution of the encoder is high than the linear displacement error will be low and the opposite is also true. Another cause can be leads crew misalignment between its nut and rotation to the centerline.

- **Angular Error :**

Angular errors are rotational errors caused by geometric inaccuracies, feedback, and misalignment in the assemblies of the structural component of the machine tool. Yaw error is the rotational error of the slide around the axis perpendicular to the plane in which the axis of motion lies. Roll error is the rotational of the slide around the axis of motion, and pitch error is the rotational error of the slide around the third orthogonal axis of the slide

- **Straightness, parallelism and orthogonally measurement :**

Straightness error is the translational error of the machine element that can occur in either of two directions orthogonal to a slide's axis of motion. The parallelism error would be the difference divided by the length between the axis of Z motion and the axis average line of the spindle. Several other errors can occur in the measurements such as the Z axis straightness error and the test arbor profile error.

- **Spindle thermal Drift:**

Thermal drift is defined in the ANST (America National Standard institutes) as " a changing distance between two objects, associated with a changing temperature distribution within the structural loop due to internal and eternal sources" from this definition of spindle error motions, three components for machine too:

1- Axial thermal drift, which is the displacement of the spindle along the Z axis.
2- Radial thermal drift, which is the displacement perpendicular to the Z axis.
3- Tilt thermal drift, which is the rotation of spindle in the X- Z plane of the machine.

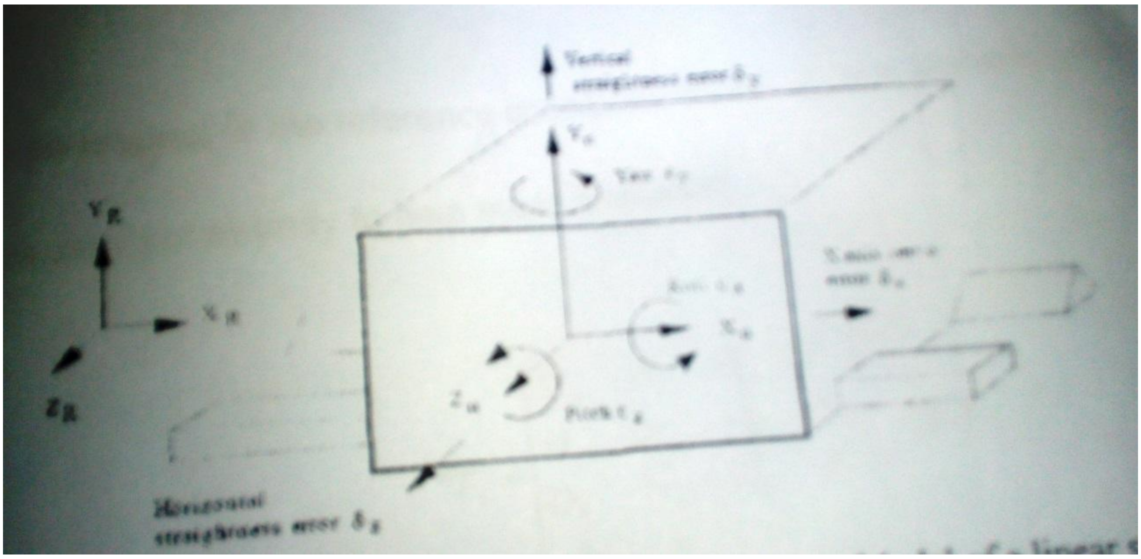


Figure (2-1) Homogeneous transformation
matrix model of a linear stage [6]

- **Homogeneous transformation matrix model of a linear stage:**

In order to determine the effects of a component's error on the position of tool point or the work piece, the spatial relationship between the two must be defined. To represent the relative position of a rigid body in three- dimensional space with respect to a given coordinate system, a 4x4 matrix is needed. This matrix represents the coordinate transformation to the reference coordinate system (Xg, YR, ZR) form that of the rigid body frame (Xn Yn Zn), and it is called the Homogeneous transformation matrix (HTM) the first three columns of HTM are direction cosines (unit vectors l,k) representing the orientation of the rigid body's Xn, Yn and Zn axes with respect to the reference coordinate frame , and their scale factors are zero [1]. The last column represents the position of the rigid body's coordinate system's origin with respect to the reference coordinate frame. P1 is scale factor, which is usually set to unit to help avoid contusion.

$$\begin{matrix} R \\ Tn = \end{matrix} \begin{bmatrix} Oix \ \ Oiy \ oiz \ Px \\ oix \ On \ On \ PY \\ Okx \ Oky \ Okz \ P2 \\ O \quad O \qquad O \quad PX \end{bmatrix} (2-1)$$

Thus the equivalent coordinates of a point in a coordinate frame n, with to a reference frame R, are

$$\begin{bmatrix} XR \\ YR \\ ZR \\ 1 \end{bmatrix} RTn \begin{bmatrix} Xn \\ Yn \\ Zn \\ 1 \end{bmatrix} \text{(2-2)}$$

For example, if the Xz Y1 coordinate system is translated by an amount x along the X axis , the HTM that transforms the coordinate of a point in the X1 Y1 Z1 coordinate frame into the XYZ reference frame is

$$XYZ = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & x & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2\text{-}3)$$

If the X1 Y1 Z1 coordinate system is translated an amount y along the Y axis, the HTM that transforms the coordinate of a point in the X1 Y1 Z1 , coordinate frame into the XYZ reference frame is

$$Xyzxiy(Z) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2\text{-}4)$$

If the X1 Y1 Z1 coordinate system is translated by an amount Z along the Z axis, the HTM that transforms the coordinate of a point in the X1 , Y1 , Z1 coordinate frame into the XYZ reference frame is

$$Xyzxiy(Z) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2\text{-}5)$$

If the X1 Y1 Z1 Coordinate system is rotated by an amount θx about X axis , the HTM that transforms the coordinate of a point in the X1 Y1 Z1 coordinate frame into X Y Z frame is

$$XYZTXiYizi= Xyzxiy(Z) = \begin{bmatrix} 1 \; 0 \; 0 \; 0 \\ 0 \;\; cos\theta xsin\theta \; x \; 0 \\ 0 \;\; cos\theta xsin\theta \; x \; 0 \\ 0 \;\; 0 \;\; 0 \; 1 \end{bmatrix} \qquad (2\text{-}6$$

If the X1 Y1 Z1 coordinate system is rotated by an amount θY about Y axis , the HTM that transforms the coordinate of a point in the X1 Y1 Z1 coordinate frame into X Y Z frame is

$$XYZ_{Txivizi} = \begin{bmatrix} cos\theta y & 0 & sin\theta y & 0 \\ 0 & 1 & 0 & 0 \\ -sin\theta y & 0 & cos\theta y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2\text{-}7)$$

If the X1 Y1 Z1 coordinate system is rotated by an amount θZ about Z axis, the HTM that transforms the coordinate of a point in the X1 Y1 Z1 coordinate frame into XYZ frame is

$$XYZT_{Xiyizi} = = \begin{bmatrix} cos\theta z & 0 \; sin\theta z & 0 \\ sin\theta z \; cos\theta z & 0 & 0 \\ 0 \; 0 \; 1 & 0 \\ 0 \; 0 \; 0 & 1 \end{bmatrix} \quad (2\text{-}8)$$

Equation (2- 9) gives the position of the (NTh axis) in terms of the reference coordinates system, when N rigid bodies are connected in series and the relative HTMS between connection axes are known,

RTN= $\prod_{m=1}^{N} m-1Tm = 0T1\ 1T2\ 1T3 \ldots \ldots \ldots$ (2-9)

2.3.: linear motion errors

Consider the case of an ideal linear movement slide of a stage

$$RTn= = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & C \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2\text{- }10)$$

For the state, the HTM that describes the effects of errors on stage emotion can be found by multiplying equations (2-1) – (2-8) in series with error terms δx, δZ, εy, and εz for x, y, z, θz, θz , and θz respectively. The same result can be obtained in the following manner.

$$En= \begin{bmatrix} 1 & -\varepsilon z & \varepsilon Y & \delta x \\ \varepsilon z & 1 & -\varepsilon x & \delta y \\ -\varepsilon y & \varepsilon x & 1 & \delta Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2\text{-}11)$$

The first column describes the orientation of the stage's X axis by defining the positioning of the tip of a unit vector, parallel to the stage's X axis. The actual HTM for linear motion stage with errors is Ratner = RrnEa [6]

$$Rtnerr = \begin{bmatrix} 1 & -\varepsilon z & \varepsilon Y & a+\delta x \\ \varepsilon z & 1 & -\varepsilon x & b+\delta y \\ -\varepsilon y & \varepsilon x & 1 & c+\delta Z \\ 0 & 0 & 0 & 1 \end{bmatrix} (2\text{-}12\_$$

The most important step in assembling the error budget for a machine is the placement of the coordinate frames and the assignment of linear and angular errors for corresponding to the axes.

The relative error HTM is the transformation in the tool point coordinate system that must be done to the tool point in order to be at the proper position on the work piece

The error correction vector with respect to the reference coordinate frame can be obtained from equation (2-13)

$$R \begin{bmatrix} PX \\ PY \\ PZ \end{bmatrix} \text{correction} = R \begin{bmatrix} PX \\ PY \\ PZ \end{bmatrix} \text{work} - R \begin{bmatrix} PX \\ PY \\ Pz \end{bmatrix} \text{tool} \ (2\text{-}13)$$

- **Motion Control system Design:**

As the intelligent element that commands the motion, the controller may by visualized as the motion system brain that generates commands and requests status reports. "Motion controllers today are mostly digital devices that calculate motion trajectories, and compare them with the actual motor or actuator position, " What explains the result is information (the reference input to the amplifier) that commands the amplifier to move the motor , Motion control systems consist of three main units:

Motion controller

Driver (motor or amplifier) device as encoder

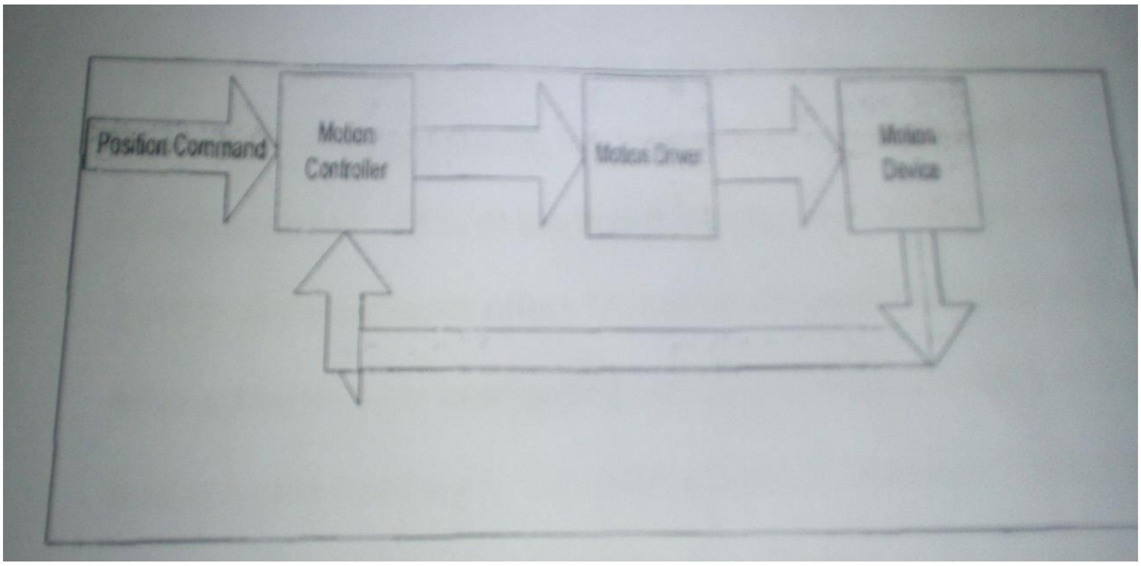


Figure (3-2) motion control systems

- **motion controller:**

In a motion system, the motion controller is used to control motion devices such as stages and actuator so that the motion controller acts as the brain of the of the system by taking the desired target positions and motion profiles and creating the trajectories for the motors

- **control system components**

Application software- you can use application software to command target positions and motion control profiles.

Amplifier r drive – amplifiers (also called drives) take the commands from the controller and generate the current required to drive or turn the motor.

Feedback device or position sensor- Apposition feedback device , usually a quadrature encoder, senses the motor position and reports the result to the controller, thereby closing the loop to the motion controller.

Configuration. – one of the first things to do is configure your system. For this, National instruments offers Measurement and Automation Explorer, an interactive tool for configuring not only motion control, but all other National instruments hardware. For motion control, measurement and Automation Explorer offers interactive testing and tuning panels that help you verify your system functionality before you program

- **Motors and mechanical Elements:**

Motors are designed to provide torque to some mechanics. These include linear slides, robotic arms, and special actuators. Motor selection and mechanical design is a critical part of designing your motion control system .

Many motor companies offer assistance in choosing the right motor, so we have servo motor for our project . After determining which technology you want to use, you need to determine the torque and inertia at the motor shaft, want to use, you need to determine the torque and inertia at the motor shaft.

Additional factors to consider when selecting your motor and other mechanics are whether an off- the- shelf actuator (such as a stage) might work for your application. Stages offer the power transmission to obtain useful rotary or linear motion without designing it yourself.

- **Feedback Devices:**

Feedback device helps the motion controller know the motor location. The most common position feedback device is the quadrature encoder, which gives positions relative to the starting point. Most motion controllers are designed to work with these types of encoders. Other feedback devices include potentiometers that give analog position feedback, tachometers that provide velocity feedback, absolute encoders for absolute position measurements, and resolvers that also give absolute position measurements. When using national instruments motion controllers, you can use quadrature encoders and potentiometers.

- **motion 1/ O**

Other / 1/O that is important in motion control includes limit switches, as shown in figure (3-4) home switches, position triggers, and position capture inputs limit switches provide information about the end of travel to help you avoid damaging your system. When a motion system hits a limit switch, it typically stops moving . Home switches, on the other hand, indicate the system home position to help you define a reference point. This is very important for applications such as pick- and – place and where you might want to trigger a system to measurements at a series of prescribed position.

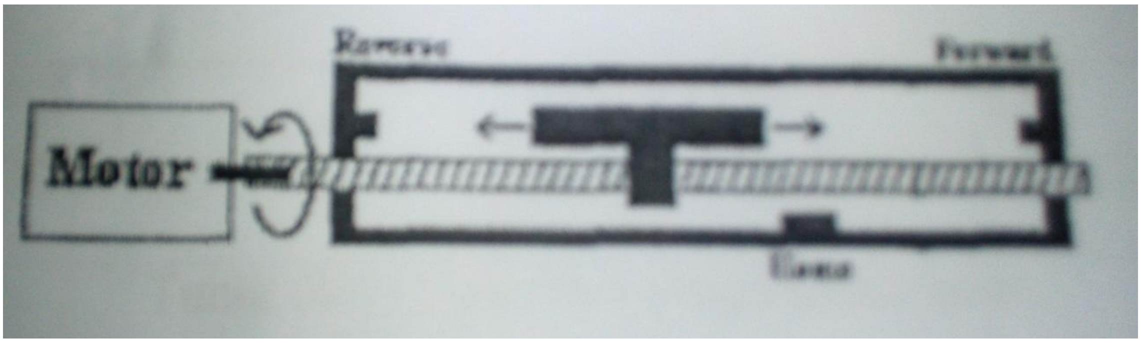


Figure (3-4) limit and home switches in a motion control system

- **components of the motorized stage**

The components of the motorized stage are shown in figure (4-1). These components were used to develop the positioning system. This system was implemented to measure the actuation and the stage movement.

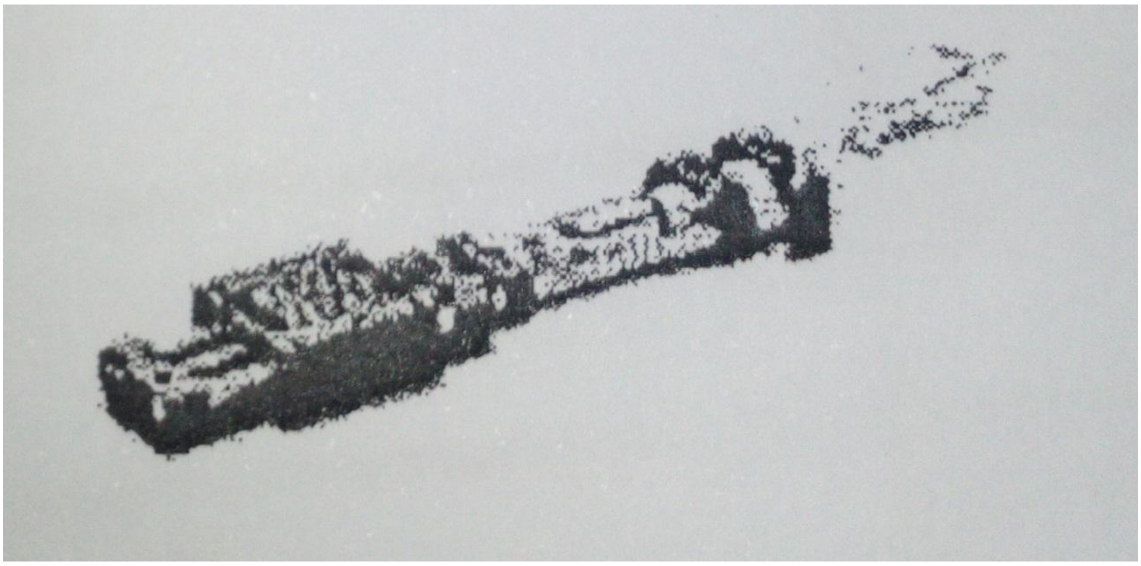
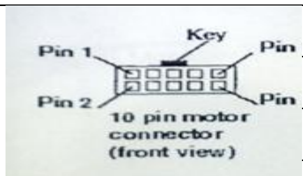


Figure (4-1) motorized stage

Motor connector pin assignments	
Motor type	MTR – 10- E
Connector type:	Dual Row IDC.
Mating Part.	Panduit Pin 057- 010- 115 (male pin socket)

Table (4 -1)motorized stage description :



PIN #	Name	Pin #	Name
1	Motor +	6	Motor -
2	Encoder + V	7	Limit Ground
3	Encoder Ch. B	8-	No Connection
4	Encoder Ch. B	9-	Reverse Limit
5	Ground (Case)	10-	Forward limit

Able (4-2) 10- pin motor connecter

Electrical Specifications	
Supply Voltage Nom. (Volts)	6
Armature Resistance (Ohm) ± 12 %	20.1
Max power output (Watts)	0.46
Max Efficiency (%)	68
No- Load Speed (rpm) ± 12%	17.600
Friction Torque (at no- load speed) (oz- in)	0.004
N0- load current (mA) ± 50%	10
Stall torque (oz- in)2	0.15
Velocity constant (rpm/ voit)	2.854
Back EMF constant (mV/ rpm)	0.350
Torque constant (oz- in/ Amp)	0.48
Armature inductance (mH)	0.060

Table (4-3) motorized stage electrical specifications

- **Drive Mechanisms:**

This section will introduce most of the more common types of drive mechanisms found in linear motion machinery, a drive system should not support any loads, with all the loads being handled by a bearing system. Topics discussed will include, but not be limited to mechanism of actuation, efficiency, accuracy, load transfer, speed, pitch, life cycle, application and maintenance.

- **Leads crew**

Leads crew is a device that converts rotary motion to linear motion. The figure (4-2) shows a sample leads crew. The two major parts are the stage slider and the lead screw. The more adjusted the thread zone, the higher the resolution of the actuation.

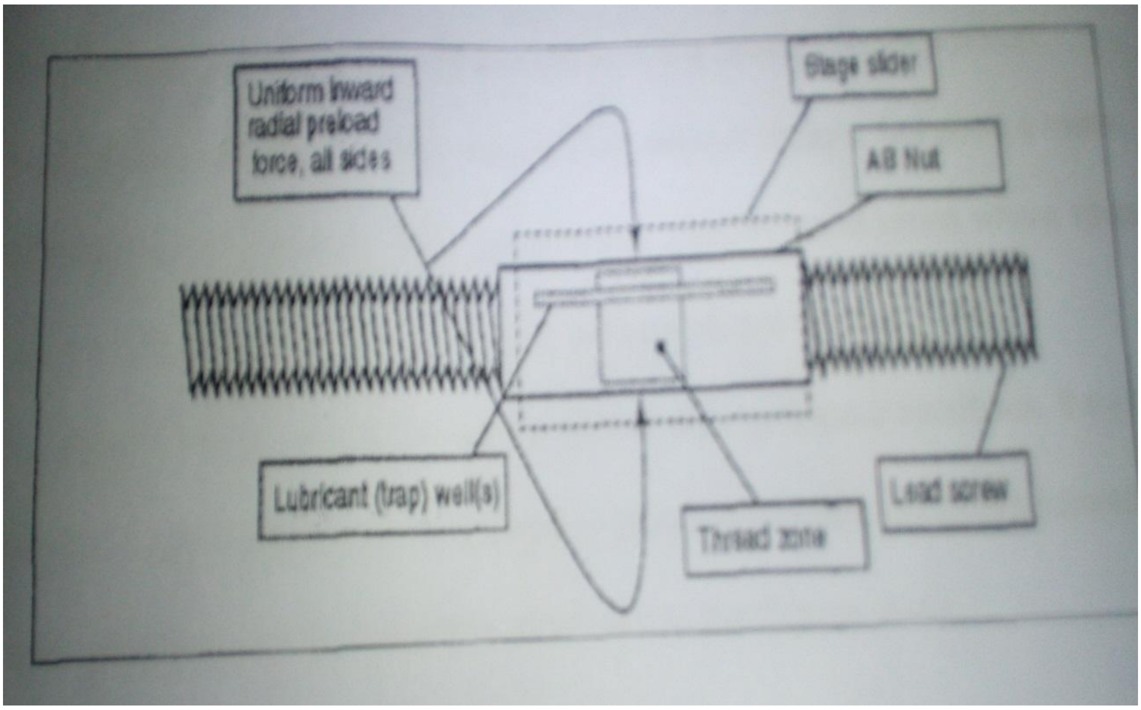


Figure (4- 2) lead screw

- **Constant Preload:**

The sliding contact thread should be as close as possible to minimize the backlash as demonstrated in the Figure (4- 3). Some resent lead screws went from standard 25- 50 micrometers to 2- 4 micrometers

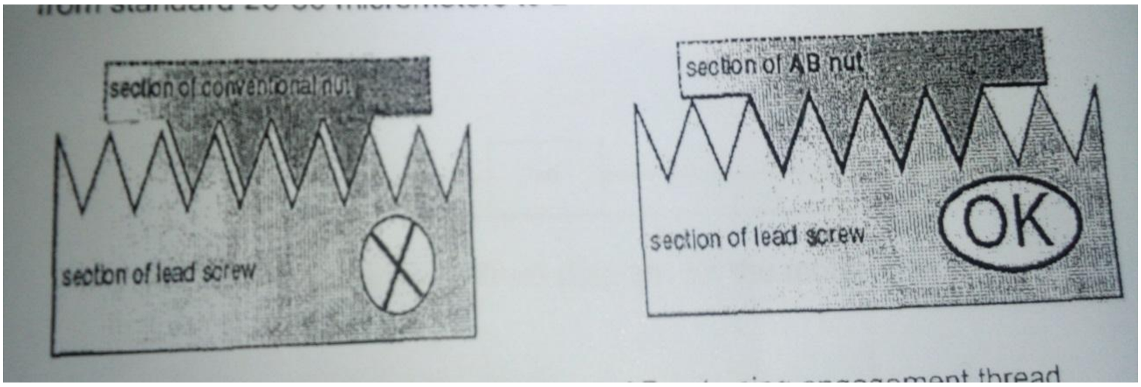


Figure (4-3) using thread conventional AB nut- using engagement thread

- **Motor:**

A motor driver receives input signals from a controller and converts them into power to drive a motor, motors turn electrical energy into mechanical energy and produce the torque required to move to the desired target position.

Servo motors are more robust than stepper motors, but pose a more difficult control problem. They are primarily used in applications where speed, power , noise level as well as velocity and positional accuracy are important. Servo motors are not functional without sensor feedback , they are designed and intended to be applied in combination with encoders (closed loop), resolvers, or tachometers as shown in the Figure (4-4)

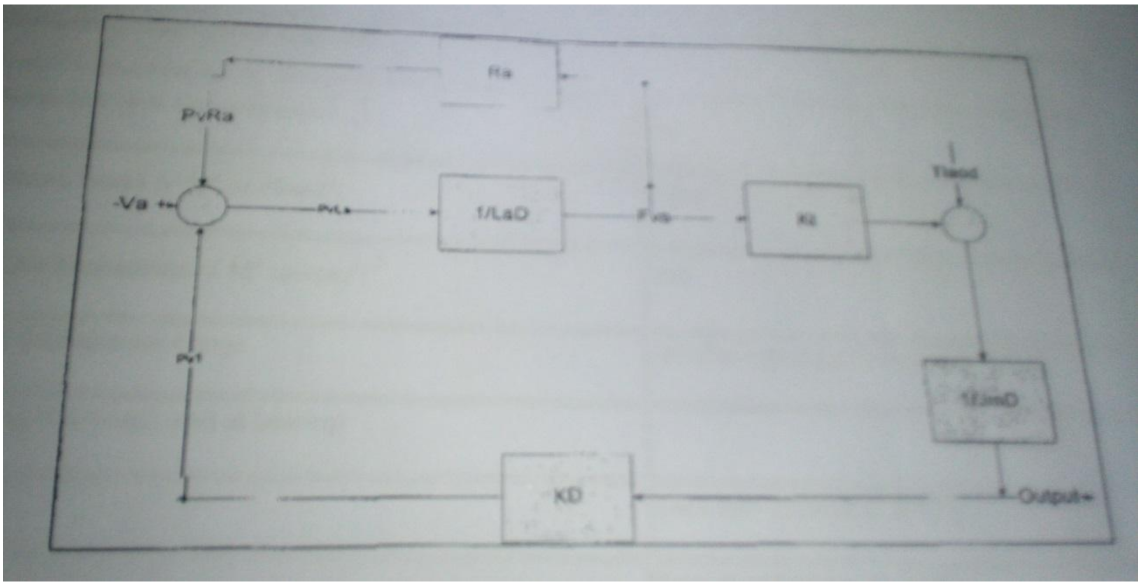


Figure (4-4) Block diagram for the motor

Mechanical specifications (motor)	
Mechanical time constant (ms)2	9
Armature inertia (x 10-6 oz- in –sec2)2	0.085
Angular acceleration (x 103 rad/ sec2)2	193
Rotor temperature range	30C to 125C (22 F to + 257 F)
Beaning play (measured at bearing)	
Redial	Less than 0.03mm (0.0012)
Axial	Less than 0.02mm (0.0079)
Thermal resistances (C/ W)	
Rotor to case	10
Case to ambient	65
Max shaft load (oz)	
Radial at 3.000 rpm (emm from bearing)	1.8 (51 grams)
Axial	72 (2.041.2 grams)
Weight (oz)	0.23 (6.5 grams)
Specified at nominal supply voltage	
Specified with shaft diameter =0.8 mm at no-load speed	

Table (4-4) motor's mechanical specifications

4.2.3 motor DC Electric (brush type)

Advantages	Disadvantages
Fast and accurate	Inherently high- speed, low- torque devices (usually needing a gear , which increases cost)
Small in size	Commentator and brushes limit life
Reversible by changing input polarity	Not self locking (brake required)
Good for position and velocity	High current at stall leads to heat generations
Inexpensive	The motor performance may suffer inefficiencies.
Easily controlled using feed back,agreeable to complicated control strategies	The brushed motor will require maintenance, as the brushes will wear and need replacement.

Table (4- 5) characteristic for servo brush type motor

4.3: Encoder (Feedback)

Encoder specifications :	
Supply voltage	5 VDC Nom
Max supply voltage	15 VDC
Operating current	5 ma nom. @ 5VDC
Signal phase shift	90
Max signal frequency	7.2 khz
Operating current	20C To + 85C (-20F to + 185 F)
Storage temp, Range	40C to + 110C (-40 F to + 230F)
Max Asymmetry	10%
Output signal type	Square wave
Signal Rise time	Less than sμs
Phase relationship	Ch. A leads ch. B when motor rotation is clockwise as viewed from shaft and
Pulses per revolution	10 (2 channels)
Quadrature	40 encoder counts

Table (4- 5) encoder specifications

A feedback device's basic function is to transform a physical parameter into an electrical signal for use by a motion controller. Common feedback devices are encoders for position feedback. The location in the motion system from which the feedback device performs its measurements directly affects the quality of the data fed back to the controller. The closer the feedback device is to the parameter being controlled, the more effective it will be in helping the controller achieve the desired result. When controlling position, for example, measuring the linear position of the stage carriage directly provides higher quality feedback than measuring the angular position of the lead screw .

- **Quadrature Encoders:**

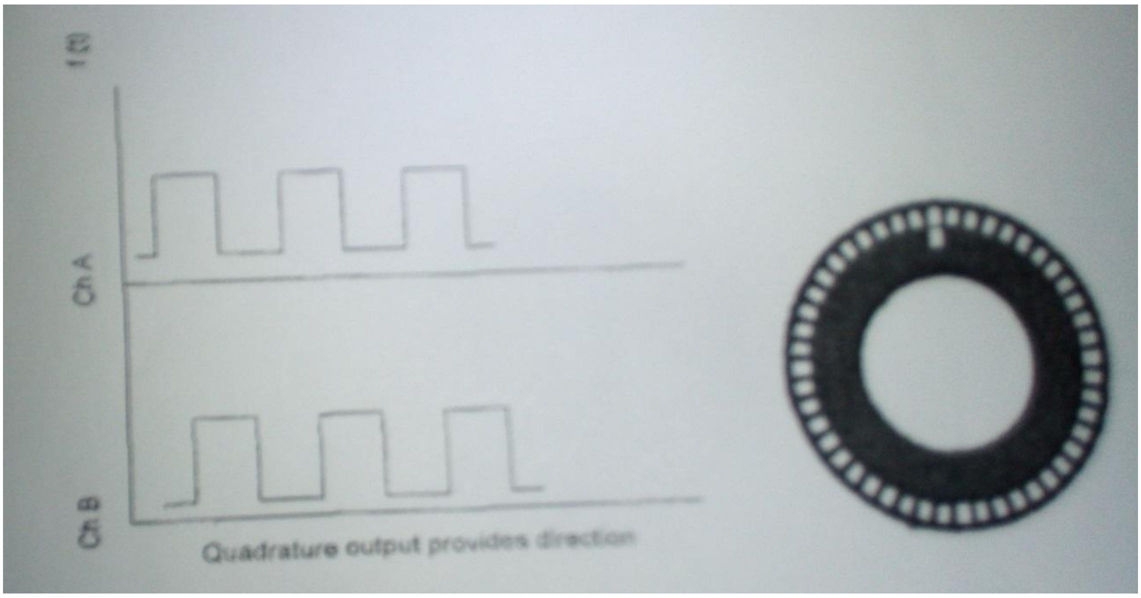


Figure (4-5)

Quadrature encoders are a particular kind of incremental encoder with of at least two output signals , commonly called channel A and channel B. As shown in figure (4- 5) , channel B is offset 90 degrees from channel A. The addition of a second channel provides direction information in the feedback signal. The ability to detect direction is critical if encoder rotation stops on a pulse edge. Without the ability to decode direction, the counter may count each transition through the rising edge of the signal and lose position .

Another benefit of the quadrature signal scheme is the ability to electronically multiply the counts during one encoder cycle. In the times- one mode, all counts are generated on the rising edges of channel A, in the times- two mode, both the rising and falling edges of channel A are used to generate counts. In the times- four mode, the rising and falling edges of channel A and channel B are used to generate counts. This increases the resolution by a factor of four.

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