CHAPTER 2
OVERVIEW OF NANOPOSITIONING SYSTEM AND CONTROL

This chapter is basically a bibliographic journey of research and development in the field of nanopositioning. This chapter attempts to describe the types of components of nanopositioning systems used in different applications. Further, this chapter also discussed the existing control techniques in the literature for nanopositioning system. Through the literature review, limitations and gaps in contemporary research are also identified which provide the motivation for the current research work.

2.1 INTRODUCTION
A nanopositioning system is a mechatronics system designed for ultra-precise positioning of a sample/object producing nanometric motion quality defined in terms of precision (motion repeatability), accuracy (lack of error) and resolution (minimum detectable incremental motion) [6,63]. Nanopositioning system is an integration of several physical components such as precise detection system and its drivers, actuator with its driver, motion guided stage and control system. Due to their unlimited resolution, piezoactuator based nanopositioning systems are widely used [6,23]. Literature survey for each component of nanopositioning system is given as follows:

2.2 NANOPOSITIONING STAGE
Since positioning stage play a crucial role in many nanotechnology applications, they have attracted considerable interest from many scholars and researchers in the recent years. Generally, most positioning stages designed for scientific research applications performed at the 10nm or less scale. A nanopositioning stage may be classified as a single-axis or multi-axes stage. Advanced technologies are constantly researched in the semiconductor industries to manufacture high quality products and highly precise positioning stage. The review of the available literature reveals that the precise positioning stage can be divided into four categories in terms of the
particular method used to drive the motion stage. These categories are: i) stick slip induced friction drive stage, ii) clamp release inchworm stage, iii) elastic deformation stage and iv) parallel stage [80].

- **Friction stage**
The moving source of the friction stage is the friction force and has the property of large travel range. In 1987, Pohl [81] utilized the principle of inertial and frictional force to drive a stage by means of piezoelectric actuator. The developed piezoelectric translation device has resolution of 0.04-0.2µm and travel speed of 0.2mm/sec.

In 1988, Niedermann et al. [82] described a nanopositioning stage based on stick slip principle which indicates a stepping resolution of 10nm and velocity of 0.4µm.

In 1990, Renner et al. [83] utilized the stick slip friction principle to develop a nanopositioning stage. The minimum displacement resolution and velocity of this stage are as low as 3nm and 0.25mm/sec. respectively.

In 1994, Smith et al. [84] developed a two dimensional nanopositioning stage having unit step displacement of approximately 10nm. In this device force generated by piezoelectric actuator is used to generate driving voltage to move the stage.

In 2005, Awtar et al. [85] describes the design of an XY flexure stage with large ranges of motion and substantially small error-motions. This flexure stage of size 300mm x 300mm exhibits a 5mm x 5mm range with cross-axis errors less than 10microns, and motion stage yaw errors within 5 micro-radians.

To obtain large dynamic range, several methods for piezo actuation in motion control are described by Breguet [86] in 2000. The maximum travel range, resolution and maximum velocity of 2DOF actuator with mechanical amplification, stick slip actuator and 6 DOF (degree of freedom) designs of micro stages are ±15mm, 200nm and ±5mm/sec. respectively. Friction stage is suffered from lower loading capability, complicated set up, low accuracy of the set up and difficult to achieve optimal performance.

- **Inchworm stage**
The multi piezo electric actuators are used to control the movement of inchworm stages. In 1985, Mamin et al. [87] described a micro positioned stage with resolution ranging from 25 to 400nm.

In 1991, Dudnikov et al. [88] used deformation of piezoelectric elements with the help of clamp release by electromagnetic force to developed high precision linear motor driven X-Y-theta positioner of accuracy, travel range and velocity as 50nm, 200mm and 4mm/sec. respectively. Single axis inchworm positioning stage having resolution, travel range and velocity of 40nm, 4mm and 300µm respectively is presented by Cusin et al. in 2000 [89]. Inchworm stages characterized by long travel range suffer from lower loading ability, complicated setup and low accuracy for the set up.

- **Elastic Deformation**

The elastic deformation of flexure provides movement of elastic deformation-stages. Previously, structures of deformation stages were performed via linear cutting. Their size was smaller, but their rigidity was not sufficient. X-Y-Z precision positioning mechanism using bimorph piezoelectric giving resolution and travel range of 0.3µm/v and ±60µm respectively is presented by Matey et al. in 1987 [90]. The design of elastic deformation-stages is suffered from very complex design and low loading ability. In 1997, Ryu et al. [91] developed a 3 axis positioning stage capable of producing displacement of 41.5 µm and 47.8 µm in x and y direction respectively and a yaw motion of approximately 1613.4µrad. A piezoelectric driven positioning stage giving displacement range of 100µm, displacement resolution of 400nm and angular deviation of 31.1 µrad. was developed by Chang et al. in 1998 [92]. In 2007, Jywe et al. [93] presented a 5- DOF nanometer-scale stage consisting of six piezo-actuators and 5 capacitive sensors to sense displacement. Further, in 2008, a 5 DOF nanometer scale stage of dimensions 200mm×200mm×35mm presented by Jywe et al. [94] has linear and rotation accuracy of 100nm and 0.004” respectively. Rigidity of elastic deformation stage is improved but again the loading ability of this scheme is also not sufficient and has very short travel range.

6DOF nanopositioning stage mechanisms discussed by Merkle in 1997 [95] are simple in Design, high stiffness and strength and have high travel range. In 1997,
Clavel et al. [96] presented the design principle and an application example of a parallel micro-robot. In 1999, Gao and Swei [97] presented the six degrees-of-freedom micro-manipulator having 17\(\mu\)m linear travel range and angular rotation of 111.6 \(\mu\)rad. The linear resolution of this manipulator is 10 nm. In 2006, Chu et al. [98] presented a nanopositioning stage which, in stepping mode is capable of performing precision positioning over an extended displacement range in incremental step sizes ranging from 70nm to 35\(\mu\)m. In the scanning mode, this stage can perform a scanning motion over a displacement range of 50\(\mu\)m with resolution less than 10nm.

From the detailed literature survey regarding development of positioning stage, it has been concluded that although inchworm-type positioning stage is characterized by long travel range, it suffer from lower loading ability, requires complicated setup and low accuracy for the set up. Conversely, the elastic deformation type stage is straightforward to control but has limited positioning travel range.

2.3 FLEXURE GUIDED STAGE

One of the key requirements of nanopositioning stage is the elimination of non-deterministic effects such as friction and backlash, which are commonly seen in bearings and transmissions that rely on rolling and sliding interfaces [6]. So, to achieve nanometric resolution, it becomes necessary to employ non contact bearing system, transmissions, sensors and actuators. Precision positioners with extended displacement range generally utilize a linear guide-way to guide the stage. To make the best use of high resolution provided by piezoelectric actuators, traditional mechanical guiding systems are not acceptable, instead flexure guided mechanism are state-of-the-art [6,56]. Flexures are the most common bearing choice for nanopositioning systems. Monolithic structure of flexures entirely eliminates the friction and backlash problem and leads subnanometer resolution. Flexure guided nanopositioning systems have emerged for high speed, high accuracy nanoscale positioning and are used in several commercial AFMs [23]. Generally, flexure based nanopositioning system are capable of producing motion range of
approximately 100µm [56,63,99]. Schitter et al. [45] developed a scanner based on piezo-stack actuators where all actuators are connected in push pull arrangement and mechanical flexure are used to decouple the lateral and transverse motion.

While existing nanopositioning systems are capable of producing motion range of several hundred microns, there is growing list of applications requiring multi-axes (XY and XYZ) nanopositioning systems that are capable of producing motion range of the order of several millimeter (approximate 10mm) over multiple axes and maintaining nanometric quality as well [100]. In 2010, Jager et al. [101] explained the operation of high precision long range three dimensional nanopositioning and nanomeasuring machine (NPM-machine) having a resolution of 0.1nm over the positioning and measuring range of 25mm×25mm×5mm. Hsien et al. [102] presents a two dimensional interferometric nanopositioning system that consists of 2 dimensional flexure stages, two dimensional heterodyne interferometer and a digital closed loop feedback control system.

To design multi-axis flexure guided nanopositioning systems, flexure guided mechanisms can be classified into two main configurations:

i) Serial Kinematics configuration.

ii) Parallel Kinematics configuration.

This arrangement also defines the degree of freedom and the degree of constraint directions of the nanopositioning stage. For example, a 2-axis XY nanopositioning system will have X and Y as degree of freedom directions and Z, Φ_X, Φ_Y and Φ_Z as degree of constraint directions. The performance measure of any nanopositioning system lies in its ability to move the motion stage along its degree of freedom directions in a controlled manner, while minimizing the motion along all other (constraint) directions.

2.3.1 Serial Kinematics

A serial kinematics can be obtained either by i) stacking one piezo-stack actuator (and sensor) in series with another actuator (sensor) to obtain the desired displacement or ii) nesting one flexure guided nanopositioner into another [46]. In serial kinematics each axis has its own platform with its own
actuator and sensor as shown in figure 2.1 which results in bulky construction. Because each sensor can only sense input from its own axis, errors caused by parasitic motion due to cross coupling effect from the other axes in the system cannot be measured and corrected which leads to cumulative error. However, the cross coupling effect can be minimized with carefully designed structure and mechanisms. These kinematic are easy to design, can be operated with simpler controllers and provide relatively high bandwidth for the fast scanning direction. However, high mechanical bandwidth can only be obtained in one axis. For raster scan operation, the serial designed nanopositioning stage with one stage of high bandwidth is sufficient. First generation serial kinematics configuration based, high bandwidth two axis nanopositioning stage (high speed scanner) used for high speed nanopositioning and scanning probe microscopy (SPM) based applications designed by K. K. Leang et al. in 2009 [46] is shown in figure 2.1. The high bandwidth x axis is nested within the low speed y axis.

Figure 2.1  First generation serial kinematics two axis nanopositioner [46]

The range of this SPM scanner is approximately 10µm×10µm. The serial kinematics configuration is preferred for SPM applications because motion along the x axis (lateral axis) is approximately 100 times faster than the slower y axis (transverse
axis). In 2009, Y. Shan et al. [103] describes the piezo based flexure guided serial
kinematics, two axis nanopositioner for scanning operation with an approximate
travel range of 10µm×10µm and is shown in figure 2.2. Furthermore B. J. Kenton et
al. in 2012 [50] presents the design and control of three axis serial kinematics high
speed nanopositioning stage that offers approximately 9µm×9 µm×1µm motion
range and kilohertz bandwidth.

![Figure 2.2 Serial kinematics arrangement [110]](image)

In 2012, A. A. Eielsen [104] discussed the repetitive control of flexure guided
nanopositioning system consisting of serial kinematics nanopositioning stage, piezo
actuator and capacitive displacement sensor.

### 2.3.2 Parallel Kinematics

The parallel kinematics designs are used to decouple the actuation effect from the
other axis. Parallel kinematics designs are based on only one moving platform. In
this configuration, all actuators (sensors) are connected in parallel to the sample
platform as shown in figure 2.3.
In XY parallel kinematics configuration, both X and Y actuators are ground mounted which results in a compact structure. All motions (no matter where it is originates from) are measured by the X sensor because there is only one common motion platform.

The spring constant $K_x$ and $K_y$ in figures 2.2 and 2.3 for both serial and parallel kinematics configuration model the stiffness of the added flexures in each direction. To achieve high resonance frequency (high bandwidth) the spring should be as stiff as possible while maintaining the low effective mass. The effective damping $C_x$ and $C_y$ appear in parallel with each spring constant.

Parallel kinematics nanopositioners possess inherent advantages over conventional serial kinematics nanopositioners in terms of high rigidity, high load carrying capacity, high accuracy, high bandwidth due to lack of moving actuator and high precision due to lack of disturbance from moving cables [100,105]. Since all actuators are fixed relative to the ground, it eliminates the inertia of the moving sample platform. If parallel kinematic configurations have symmetrical structure (mechanical dynamics of both lateral and transverse axes are similar) the scan direction can be chosen arbitrarily [106]. However, the cross coupling between the X and Y axes can be more difficult to deal with as compared to the serial kinematics. The cross coupling effect can be minimized as low as -70dB to -35dB by properly designed flexures [23]. Parallel kinematics XY nanopositioners are well suited for multi-axis nanopositioning applications because of their ground mounted actuators, thus avoiding large masses and moving cables [53,107].
Actuated Parallel Kinematics is shown in figure 2.4. For the raster scanning, the motion along one axis is considerably faster than the other. For this reason serial kinematics configuration with one high speed stage is sufficient. Since, high bandwidth, high power piezo amplifiers are required only for high speed axis, it is more cost effective to design and manufacture. Therefore, for high speed SPM applications serial kinematics nanopositioners have been considered [40,108].

Conversely, Parallel kinematics less sensitive to the temperature variation and are well suited for highly accurate multi axis and fast nanopositioning applications. But high speed parallel kinematic nanopositioners require high power and high bandwidth piezo amplifier and control hardware for all directions which in turns increase the overall cost of the system [23]. In 2010, Sebastian et al. [109] presents the design analysis fabrication and testing of high bandwidth piezoe- driven parallel kinematics nanopositioning XY stage. This nanopositioning stage is capable of producing 15µm motion along each axis with a resolution of about 1mm.

Nanorobotics is currently a much studied field and integrates together various disciplines including nanofabrication processes used to produce nano robots, nanoactuators, nanosensors and nano scale physical modeling. Nanorobotics manipulation technologies, including nanoscale assembly of units, biological cells
and molecules manipulation and types of robots performing these tasks also form a part of nanorobotics. Nanorobotics manipulation system can be used for nanoassembly, biotechnology, construction and characterization of nano-electromechanical systems [110].

There are practical limitations associated with the individual physical components of nanopositioning system as well as their integration. Physical components suffer from their inherent performance limitations in their ability to achieve the desired dynamic range. For multi axis system, the mechanical attributes of each component such as coupling between two axis of parallel kinematics configuration, fixed axis of sensing and actuation, leads to a serious challenges in terms of overall system integration. In 2010, Shorya et al. [100] highlights the several challenges that exist in the physical and control system design of the multiple axis flexure based XY nanopositioning stage capable of large dynamic range. To design a nanopositioning system of very high accuracy, it is necessary to overcome these system integration challenges by taken into account the flexure bearing, actuators and sensors.

### 2.4 SENSORS FOR NANOPositionING SYSTEM

The position sensing mechanism plays an important role for speed, high resolution motion control and absolute position accuracy of various nanopositioning systems. Two techniques to measure the displacement of the piezo electric motion systems are [59]:

i) Indirect (Inferred) metrology

ii) Direct metrology

In indirect metrology, the inference of the position of the moving platform is made by measuring the position or deformation of the actuator or any other component in the drive stage. In this scheme, motion inaccuracies which arise between the drive stage and motion platform cannot be accounted for.
In direct metrology, the motion of the moving platform is made with the interferometer or capacitive sensor. This scheme is more accurate and more suited to applications where absolute measurement of moving platform is needed.

In multi axis positioning system parallel and serial metrology exists for parallel and serial kinematics nanopositioners. With parallel metrology, all sensors measure the position of the same moving platform against the same stationary reference. In serial metrology, the reference plane of one or more sensors is moved by one or more actuators. In this scheme, off-axis motion of any moving reference cannot be measured and hence cannot be accounted for.

For ultra-high precise positioning applications, sensors based on variety of positioning sensing techniques such as piezo-resistive, optical, capacitive, thermal and inductive are widely used [36,59-65]. Accordingly, the sensor used for nanopositioning applications are

1) Capacitive Sensors
2) Piezo Sensors
3) Thermal Sensors
4) Inductive Sensors
5) Optical Sensors

Simplicity, linearity, bandwidth, resolution of the sensors and working environment are important criteria for the selection of nanopositioning system. Various characteristics of the position sensor i.e linearity, bandwidth, resolution and drift, are described by A.J. Fleming in 2013 [111]. Sensors must be able to measure displacement to the subnanometer level and must display linearity with no creep or hysteresis. The readout from the position sensor controls the voltage on the piezoelectric stack actuator through a closed-loop-feedback system, which eliminates the effects of creep and hysteresis due to the PZT.

2.4.1 Capacitive Sensor

Most common displacement sensors are based on the capacitance changes involves parallel plate construction where one of the plates is movable and other is fixed. Displacement can be measured by the capacitance of this arrangement which
depends on the plate spacing and plate area. Area can be varied by letting the displacement vary the overlap between the plates. The change in capacitance directly relates to the distance measurement with appropriate calibration to account for the nonlinearity effects [112]. Since the capacitance is inversely proportional to the distance between the plates, the motion of positioning stage changes the distance d between the plates, the resultant change in capacitance C is measured to determine d.

\[ C = \varepsilon_0 \varepsilon_r \frac{A}{d} \]  

(2.1)

Where A is the area of the plates, d is the distance between the plates, \( \varepsilon_0 \) is the dielectric constant of the free space and \( \varepsilon_r \) is the relative dielectric constant of the material between the plates. The displacement range of changing gap capacitive sensor is limited as compared to the change in area configuration. However, the changing gap-configuration is relatively more sensitive than the changing area configuration [113]. Two and three plate capacitors based upon changing gap configuration and changing area configurations are available shown in figure 2.5(a) and (b) respectively. With a two plate configuration, changes in absolute capacitance are measured which are corresponds to motion of sample or positioning stage.

**Figure 2.5** Two and three plate configuration of capacitive sensor

a) Changing gap configuration  b) Changing area configuration.
Differential changes in capacitance can be measured with a three-plate configuration. Dynamic measurement range of the 3-plate configuration is more as compared to a 2-plate configuration. A position sensor for the xyz-stages used for various kinds of probe-based microscopy applications using the 2-plate gap-closing configuration is manufactured by Physiks instruments and Queensgate [56]. Capacitive position sensors manufactured by these companies have resolutions of 0.01 nm over 1 mm range, extremely high long term stability of 0.1 nm/3 hours and bandwidth of 10 KHz. The nominal capacitance is approximately 10 Pf [56]. The challenges for the design of ultrasensitive capacitive micrometer are to eliminate all unwanted environmental variations due to pressure, temperature and electric component changes and be able to detect very small variations of plate capacitance. In 1973, Jones and Richards [114] have demonstrated a detectable static displacement of $10^{-13}$ m and a corresponding resolution limited to $0.3 \times 10^{-18}$ F for a 3-plate changing gap configuration. However, range of motion is limited and there is a common trade-off between high resolution and large-displacement range. Changing area configuration is preferred for large-range displacement sensing. For high dynamic range this configuration can be replicated many times with the addition of a counting circuit to count the plates. Baxter [113] reports capacitive multiple plate systems which combine high resolution with long measurement range. In 1981, Kosel [115] described a linear capacitive transducer having resolution of 4 pm and range of 3 cm range. Klaasen and Van Peppen [116] describe a printed circuit board realization of a multiple plate capacitive displacement sensors having resolution of better than 25 nm in a measurement span of about 1 cm and a non-linearity smaller than 2 µm.

Cheung et al and Legtenberg [117-118] have used micromachined comb-structure capacitive sensors to detect displacements. Comb-sensors are however always limited in dynamic sensing range i.e. ratio of range over resolution. Cheung is able to measure lateral positions with 0.01 µm estimation error using state-variable feedback control.

Capacitive sensors have high accuracy, long displacement range, and compatibility of the micromachining and fabrication process, the wide range of
interfacing possibilities and electronic signal manipulation and potential for parallelism. A less favorable property of capacitive sensors is the occurrence of parasitic electrostatic forces between sensor plates and the ever present parasitic capacitances.

Very recently, displacement resolutions of less than 1 nm using silicon displacement sensors based on the conduction of heat between two surfaces through the ambient air have also demonstrated [6]. Real capacitance sensors are nonlinear because of their finite size and the difficulties in getting the plates exactly parallel. Creep and drift can be reduced with strain-free mounting techniques and with careful selection of material having low value of thermal expansion.

To obtained nanoscale resolution, an embedded on chip capacitive displacement sensor integrated in a thermal actuated nanopositioner is described by L.L. Chu et al. and J. Lee et al. [119-120]. Capacitive sensors are unique in ability to tolerate large off axis displacements and are highly suitable for multi axis nanopositioning system. But their measurement range is limited to only 10 to 100µm making them unsuitable for large range nanopositioning [100]. In 2008, X. Huang et al. [121] make the use of MEMS capacitive sensor for electromagnetic scanner having X/Y motion capability with linear range stroke of 300µm.

Ju ll Lee [120] presents a micro-electro-mechanical systems (MEMS) capacitive position sensor for nanopositioning applications in Probe storage systems. The sensor system is designed to develop a high-precision X-Y linear and rotational position sensor with a minimum sensor area and a large range of movements at high speed.

Capacitive sensors typically weigh grams and have dimensions of centimeters, limiting the speed and size of nanopositioners. Moreover, smaller the capacitance, the capacitive sensor becomes more nonlinear and less sensitive.

2.4.2 Piezoresistive Sensor

Piezo-resistive sensors, on the other hand, sense motion through a change in the details of its bandgap, which is recorded as a change in resistance. Since piezo resistive sensors weigh only milligrams and have dimensions of millimeters, it is
easy to integrate them into miniaturized stages. The reduced mass allows a positioning stage to operate faster than the same stage with a capacitance sensor. This effect becomes larger as the overall dimensions of the stage decreases. Mad City Labs [99] has built and tested more than 25 nanopositioner designs that use piezoresistive sensors. The piezo resistive sensors have low noise due to the sensors’ low resistance and high sensitivity. The devices also are highly linear. Piezo-resistive-based nanopositioner can have range of motion equal to 100 µm and a measured nonlinearity of less than 0.05 percent. Since hysteresis and creep of the stage also are almost negligible, linearity corrections are not needed for a piezo-resistive sensor so software or firmware overhead can be reduced, translating to higher speeds in nanopositioning. A number of high-speed piezo-resistive-sensor-based nanopositioners also have been tested by Mad City Lab [99]. One example is a large two-axis nanopositioning system built for microscopes that can operate continuously at a velocity of 130 mm/s. As the requirements for nanopositioning increasingly demands smaller and higher-speed systems, piezo-resistive sensors become positioning standards.

2.4.3 Optical Sensor
Optical sensors are popular for measuring position and displacement. The advantages are simplicity of application and relative long operating distances. They are relatively insensitive to stray magnetic fields and electrostatic interferences and therefore quite suitable for many sensitive applications. A light source, a photodetector and a light guidance or transport medium are the three essential components of an optical position sensor.

2.4.4 Thermal Position Sensor
Thermal displacement sensors are based on a concept of change in heat flow which results in changes in resistance of a temperature dependent resistive heating element. The heat flow is proportional to surface area and inversely proportional to the gap distance. A larger gap distance will decrease the heat flow, the heater temperature will increase and thus the heater resistance will increase. The sensing element is a
resistive heater made from moderately doped Silicon and supported by legs made from highly doped Silicon that acts as electrical leads.

The thermal sensing principle does not have the parasitic forces as present with capacitive sensing, only possible mechanical deformation effects due to thermal expansion. Similar to parasitic capacitance with capacitive sensing, the thermal sensing principle is always accompanied with parasitic effects e.g. changing heat sink temperature, heat leaks and drift. To minimize drift effect, the sensors are operated in pairs using differential configuration. The thermo-mechanical probe-based sensors show fast time-responses. However, in general thermal transducer principles are considered to be relatively slow principles. The power consumption is uncertain and likely to be higher than that of capacitive sensors.

A novel micro-machined silicon displacement sensor (thermal sensor) based on the conduction of heat between two surfaces through the ambient air is described by M.A. Lantz [122]. Using this thermal sensor displacement resolution of less than 1 nm and a dynamic range of more than 100 µm can be achieved in a 10 KHz bandwidth. To minimize drift effect, the sensors are operated in pairs, using a differential measurement configuration. The power consumption of these sensors is of the order of 10 mW per sensor and the measured time response is of approximately 100 µs.

Sebastian et al. [31] demonstrated the use of two voice coil actuators to actuate the scanner in the X and Y directions and two pairs of thermal position sensors used to provide X-Y position information of the scanner. The sensors consist of thermally isolated, resistive strip heaters made from moderately doped silicon and are positioned directly above the scan stage. Displacement of the scan stage translates into a change in the temperature of these heaters and thus a change in their electrical resistance.

Paper presented by J.Chow et al. [123] describes a novel concept that employs a thermal-based approach for in-situ displacement sensing of electro-thermal actuators. A device consisting of an in-plane electro-thermal actuator and a thermal sensor are monolithically fabricated. Analytical models are developed for
both the actuator and the thermal sensor and experimental results shows that the
sensor achieved high linearity and sensitivity of the order of 4.5 nm/Ω.

Compared with the capacitive sensor, a thermal sensor is much more compact
and can be easily integrated with the actuators in MEMS devices [124]. Compared
with the other MEMS actuators, electrothermal actuators consume more power and
do not offer certain advantage. However, they can generate large forces, operate
under low voltage and give a high variation in resistance due to stiff structure [125].

2.4.5 Magneto Resistive Sensor
A novel sensing concept based on the magneto-resistance (MR) has been developed
that shows great promise towards achieving high-bandwidth and high-resolution
position sensing. The key idea here is to translate the motion of the scanner into a
change in the magnetic field as seen by an MR sensor [29,31].

It consists of two active and two shielded GMR sensing elements configured
into a Wheatstone bridge. The sensor is sensitive in one direction in its plane, with a
cosine scale-off in sensitivity as it is rotated away from its sensing direction. Two
GMR sensors are mounted on the stationary frame of the scanner, one each for the x-
and y axis. Two permanent magnets are glued to the moving scan table, again one for
each axis, directly above the corresponding GMR sensors. As the scan table moves
along each axis, the magnetic field seen by the corresponding GMR sensor changes.
The resulting electrical resistance change is read using an analog low-noise circuitry.
Because of the physical separation between the magnets and their orthogonal
configuration, the coupling between the sensors for the x- and the y-axis is minimal.
In this configuration sensitivity and spatial resolution of about 75 mV/m and 2.36nm
was achieved. This is truly remarkable, given the simplicity of this sensing concept
and the fact that this resolution is available over a bandwidth of 10 KHz [31].

2.4.6 Inductive Sensor
Most commonly used inductive sensor is LVDT (Linear variable Differential
transformer). LVDT is an electrical transducer which can be used to measure linear
displacement with a range of 1mm to over 50cm. It does not require an electrical
contact between the moving part and the coil assembly, but instead based on electromagnetic coupling. LVDTs are very popular in military and industrial applications due to their robustness, infinitesimal resolution, large range, inherently frictionless, and virtually infinite life when properly used. LVDTs are most suitable for one degree of freedom applications with displacement range of approximately 1mm or more. The major limitations of LVDTs include limited bandwidth sensitivity to lateral motion. Detail description of LVDT is given in chapter 3.

A capacitive sensor, LVDT, a position sensitive detector (PSD) can detect displacement down to subnanometer range, but limited to maximum measurable displacement of few hundred micrometers [56].

Among all sensors used for nanopositioning applications, capacitive sensors are widely used because of its unlimited resolution, simplicity of the sensor element itself, low power consumption, high temperature stability and excellent noise performance when operated over a low bandwidth [56]. Capacitive sensors provide a relatively simple technique to implement non contact measurement of geometric quantities such as distance, displacement, position, length, separation or other linear dimensions. In addition, intrinsically capacitor sensors have zero hysteresis and zero dead band error [63]. LVDT and linear optical encoder sensors provide large measurement range, nanometric resolution, offers non contact frictionless operation and have fixed sensing axis defined by their geometry. These sensors are restricted to measurement along the sensing axis only and are intolerant to any off axis motion deviation [66] Y. Shan et al and M. V. Salapaka [36] describe the use of inductive sensor for displacement measurement. K. K. Leang et al. and S. Devasia [48-49] discussed the use of optical sensor to measure the lateral displacement of the scanner.

2.5 ACTUATORS FOR NANOPositionING SYSTEM
Actuators are used to convert electrical signal generated by controllers into non electrical signal. Actuators used for nanopositioning system must have high resolution and bandwidth. Power consumption, dimensions, weight, force and displacement range under diverse working conditions of the actuators are the
important design parameters to be considered during particular application of the nanopositioning system. Some of the actuators perform well for some characteristics, but not for all characteristics. MEMS based electrostatic, MEMS based electrostatic surface, MEMS based electrostatic shuffle, MEMS based thermal, MEMS based electromagnetic, magnetoresistive, resistive, capacitive, piezoelectric actuators are some important actuators used for nanopositioning applications. As piezoelectric actuators can provide frictionless motion, produce large forces and ideally unlimited resolution, they are ideal choice for most nanopositioning system.

In a survey conducted by S. Devasia et al. [6] in 2007 different types of the actuators utilized in nanopositioning system depend upon type of material such as piezoelectric, electrostatic, electromagnetic, magnetostrictive and thermal actuators [6] had been discussed. The electromagnetic actuator generates forces by the flow of current through coils of wires in the presence of a magnetic field, which have the advantages of low power consumption and large travel range [6]. Thermal mechanical actuator can be replaced by electromagnetic actuator as the device size decreases [23].

Magnetostrictive actuators made up of magnetostrictive or piezomagnetic material offer the larger displacement range and ratio of mass per unit stress compared with piezoelectric actuators. Electrostatic actuators consisting of interdigitated comb actuators and parallel-plates actuators can be used as the secondary actuators in dual stage servo systems of hard-disk drives because of the ease of fabrication [6,23]. Potential problems associated with these actuators are their high power consumption and relative weak force.

Magnetic and piezoelectric actuators are the most common type of actuators used for nanopositioning applications. Piezoelectric actuators are undoubtedly used for nanopositioning applications because of high resolution, very high speed and compact size [6]. A. J. Fleming [126] experimentally shows that the resolution of a piezoelectric tube nanopositioner is 2.1 nm with a closed-loop bandwidth of 100Hz.

Dual stage actuation (DSA) systems can also be used to achieve both large stroke and high precision positioning. Shingo et al. [127] describe DSA system
capable to position over a long range of 500mm at ±15 nanometer static precision with a settling time of only 1.72 seconds.

2.6 CONTROL OF NANOPOSITIONING SYSTEM

The desired characteristics of nanopositioning system (nanopositioners) are extremely high resolution, accuracy, stability, fast response with zero or very low overshoot [6]. The performance characteristics of nanopositioning system are greatly affected by induced structural vibrations, mechanical dynamics of the motion mechanism (Flexure), cross coupling behavior, external disturbances, drift due to the temperature variations and presence of nonlinearities (hysteresis and creep) in piezoelectric actuator [23,68]. The vibration effect drastically limits the operating bandwidth and is often caused by the command signal exciting the flexible modes of the mechanical structure [42]. Hysteresis, a nonlinear behavior between the input (voltage) and output (displacement) of the piezoelectric actuator during long range applications causes SPM image distortion, instability of the closed loop and loss in calibration [40,79,128].

The main challenge to design robust nanopositioning system come from i) Flexure stage dynamic that limits the bandwidth of the nanopositioning stage, ii) difficulty to model non linearities of piezoelectric actuator and iii) sensor noise management issue in control feedback that potentially decrease the tracking resolution of the device. Large efforts have been made to counter these challenges such as: i) using harder piezoceramics which have smaller non linearity effect at the cost of reduced travel range ii) compensating the adverse effect of inherent nonlinearities of piezoelectric actuator by careful modeling of these non-linearities iii) using control techniques to improve nanopositioning system’s performance.

Control plays as important role to achieve desired characteristics of a nanopositioning system. To meet certain performance characteristics, the design of a controller to alter or modify the behavior and response of an unknown system can be a tedious and challenging problem. The important control approaches for achieving precise positioning along with high resolution for nanopositioning systems fall under two main categories [6,49,67,129] such as
• Feedback Control Scheme
• Feedforward Control Scheme

Each category has its advantages and disadvantages. In this section, detailed review of some control techniques used for nanopositioning system has been discussed.

2.6.1 Feedback Control Schemes

The most popular technique for the control of commercial nanopositioning system is sensor based feedback using an integral or proportional integral control. These controllers are simple, easy implementation and maintenance procedures, robust to modeling error, effectively reduce the piezoelectric nonlinearities at low frequencies and above all reliable to provide high gain at low frequency [130]. Block diagram of feedback control system is shown in figure 2.6.

![Figure 2.6 Feedback control system](image)

Feedback increases the positioning bandwidth of the closed loop piezoelectric actuators by flattening the frequency response in the region that contains the desired position trajectory’s frequency content. In the applications where high performance and accuracy are not critical, constitutive nonlinearities of piezoelectric nanopositioning stage can be compensated by standard Proportional Integral (PI) or proportional double integral (PII) or Proportional Integral-derivative (PID) controllers [131-133].

The main issue for the piezoelectric actuator based nanopositioning system are the low bandwidth, low gain margin and inherent non-linearities of piezoelectric actuator. Various feedback control schemes to for achieving high bandwidth, high
gain margin and to compensate inherent non linearities of piezoelectric actuator based nanopositioning system are as follows:

### 2.6.2 Controllers to Improve Gain Margin

Positioning errors in Piezo-actuator based nanopositioning system can be reduced by using feedback controllers, but a problem by using feedback- controllers is the low-gain margin inherent in piezo-actuators. Piezoelectric actuator has low gain margins due to structural damping (i.e. sharp resonant peak which results in high Quality factor) and additional piezo dynamics (poles) which together pull the phase response of the system below -180° mark and give rise to low gain margin [67]. This low gain margin indicates that with a proportional feedback controller, the proportional gain is restricted to be very less (less than 0.14) for stability of the closed loop system and such low-gain feedback controllers do not lead to significant improvement in the tracking response when compared to the open-loop system.

For relatively low speed positioning applications, PID controller is adequate, but as the scanning speed increases, significant tracking error exists due to system dynamics. At high frequencies, precision positioning using feedback controller can also be achieved if gain of the feedback controller is chosen sufficiently large at those frequencies to overcome vibration induced error. The low gain margin problem of piezoelectric actuator and to enable the use of high-gain feedback control, the gain margin can be increased by modifying the first (sharp) resonant peak of the open loop nanopositioning system with notch or inversion filter as shown in figure 2.7.

![Feedback control with notch filter](image)

Figure 2.7 Feedback control with notch filter
Notch filters are used to increase the gain margin of the system and allow the use of higher gain feedback needed to improve the precision [134-135]. It is experimentally proved that significant improvement in the closed loop performance of piezoelectric actuator even at high frequency can be achieved by the use of feedback controller with notch filter. High gain feedback control scheme improve the closed loop response substantially and significantly reduces the effect of hysteresis and creep nonlinearities [68,76]. With high gain feedback controller, there are limitations in achieving improvements in positioning performance as this method is effective only where system parameters do not change.

### 2.6.3 Controllers for Improvement in Closed Loop Bandwidth

Closed loop bandwidth of nanopositioning system using integral tracking controller is limited by the presence of highly resonant mode. The factor limiting the maximum feedback gain and closed loop bandwidth is gain margin. The maximum allowable closed loop bandwidth is equal to the product of twice the damping ratio $\xi$ and natural frequency $\omega_n$. The damping ratio is usually in the order of 0.01, so the maximum allowable closed loop bandwidth is only 2% of the resonant frequency [129]. Increase in the bandwidth of nanopositioning stage can be achieved by improving the mechanical design and by implementing the various control algorithms on the nanopositioning system [74]. The closed loop bandwidth can be improved either

i) by inversion of dynamic mode

ii) by using damping control

By inversion of dynamic mode using notch or inversion filter which can provide an excellent closed loop bandwidth up to or greater than resonance frequency and is simple to implement. But it requires the accurate system model. Moreover, inversion based feedback controller becomes unstable when the resonance frequency of the system decreases. In many applications, this is not acceptable because the load and resonance frequency of the nanopositioner may vary significantly. In such situations high performance inversion based feedback
controllers are used where resonance frequency is stable and feedback controllers are frequently calibrated [136].

By using damping control where the objective of the controller is to artificially increase the damping ratio of the system by using a feedback loop. The increase in damping ratio $\xi$ allows a proportional increase in feedback gain and hence the bandwidth of the system. Unlike inversion scheme, damping control scheme is insensitive or less sensitive to variation in resonance frequency and provides better rejection of external disturbances, but it alone cannot increase the bandwidth beyond the resonance frequency [6].

2.6.4 Controllers for Lightly Damped Vibration Mode
Nanopositioning systems consisting of piezoelectric actuators have lightly damped, low frequency resonance mode in their frequency response. The main problem of high bandwidth tracking control due to lightly damped vibration mode can be overcome by increasing the damping and hence gain margin in the structure. The sensitivity due to these modes can be reduced by using the actuator to increase the damping in the structure. Because of self-sensing property, piezoelectric actuators can be used both as actuator and sensor. In direct piezoelectric effect, charge is produced when stress is applied and in reverse piezoelectric effect, strain is produced on the application of electric field to the piezoelectric actuator. Without additional sensor, damping in the structure can be introduced by using the charge produced when piezoelectric actuator is used in direct piezoelectric mode [137-138]. The additional advantage of this approach is that there is very little or no increase in noise due to sensor in the feedback path. Damping can also be introduced in the active structure by using several control schemes and hence transient response of the nanopositioning system can be improved. Among them resonant control [139-140], Integral resonant control (IRC), Passive shunt damping, positive position feedback (PPF), integral force feedback are some techniques which can be used to introduced damping in the structure and are demonstrated successfully in literature [141-146].

Reference tracking performance and bandwidth of nanopositioners can be further improved by using damping and tracking control schemes. In damping
control scheme, this can be done by coupling it with integral action [74, 129-130]. Reduction of the dominant resonant peak of the system leads to increase in gain margin, enabling higher gain to be used for disturbance rejecting integral control law [130]. Because of significant disturbance rejection, adverse effects of creep and hysteresis can be reduced significantly.

2.6.5 Controllers for Compensation of Nonlinearities
Positioning precision in nanopositioning system using piezoelectric actuators is limited due to creep effect when positioning is needed over extended period of time, due to hysteresis non-linearity for long range operation and due to induced vibrations during high speed positioning. Creep adversely affects the accuracy particularly for high speed positioning applications. Creep effect can be compensated by employing Feedback control scheme and feedforward control schemes in the nanopositioning system.

Hysteresis causes SPM image distortion [59,125], instability of the closed loop and loss in calibration [123,130]. Hysteresis can also affect the stability and tracking performance of a closed loop controller, especially when the controller is designed around a linear model. It can be avoided by operating the nanopositioner over a small range (less than 10% of its full range) but this approach limits the ability of actuator to operate over long range with sub nanometer resolution. Another alternative to mitigate hysteresis nonlinearity of piezoelectric actuator is the control which plays an important role in achieving high precision, high resolution, high bandwidth at high speed [40]. To compensate all these three nonlinear effects, both feedback and Feedforward control techniques can be used, but in general integral feedback control [56], high gain feedback control [67] and force feedback control [130] have been used to reduced these nonlinearities.

2.6.5.a Feedback Control
As explained in section 2.5.1.a, notch filter can be used to improve the gain margin of the system. By achieving relatively high gain by cascading a notch filter, a feedback controller can be used to compensate creep and hysteresis effects without
modeling such complicated behaviors. Moreover, feedback controllers are robust to parameter variation such as change in the system’s gain factor. High gain feedback control improves the closed loop response significantly and hysteresis and creep can be reduced to about 80% and 86% respectively [67-68].

2.6.5.b Model Based Feedforward Control

Although feedback control can compensate creep and hysteresis effects effectively, it provides limited dynamic compensation at high scan rates. However, the performance of such systems can be improved substantially by integrating feedforward inputs. Specifically, the inversion-based approach significantly improves the positioning precision at high scan rates and also increases the system’s bandwidth. Therefore, the integrated approach provides a means of achieving precise positioning over a wider range of scan rates and displacements.

Among all methods to reduce hysteresis in piezoelectric based nanopositioners, feedforward inverse compensation technique in which inverse mathematical model of the hysteresis non-linearity is used to determine the hysteresis compensation input. Such inverse of hysteresis is sufficient during low frequency operation because creep can be corrected using feedback control and vibration effect is not significant at low frequencies [6]. Model based feedforward control to compensate both hysteresis and dynamic effect at high scanning frequency is proposed by K.K. Leang et al. [49] in 2009 is shown in figure 2.8. In this scheme, similar to hysteresis compensation, the mathematical model of the system’s linear dynamics ($G'$ of figure 1.7 Chapter 1) can be inverted to determine vibration compensation input for piezoelectric based nanopositioners. This linear model of Piezoelectric actuator’s dynamics $G'$ is augmented with the hysteresis inverse $H^{-1}$ to invert the dynamics of entire system $H^{-1}(G'^{-1})$.

![Figure 2.8 Inversion based feedforward control](image-url)
In figure 2.8, $H^1$ is the feedforward hysteresis compensator. To isolate the hysteresis behaviour, creep and vibration effect must be compensated [68]. In 2006, K.K. Leang et al. [76] modeled and compensated the effect of creep in piezoelectric actuators. The schematic diagram for creep compensation is shown in figure 2.9.

![Figure 2.9 Creep compensation for piezo-actuator based positioning system](image)

An integrated inversion based approach can also be used to obtain significant improvement in positioning precision and operating speed [40]. Extremely low noise and high stability can be achieved by integrated resistive strain gauge and piezoelectric force sensors used to estimate displacement. [130].

### 2.6.5.c PI Feedback Control Integrated with Feedforward Control

Since an integral action provides high gain at low frequencies, so to achieve precise positioning at low frequencies, it can be used to overcome creep and hysteresis (Vibrations are not effective at low frequencies). Chih et al. [142] compensate the hysteresis non-linearity of the piezo electric actuator by using PI feedback controller associated with feedforward compensator based on hysteresis observer as shown in figure 2.10. Inverse hysteresis compensator can be used as feedforward controller to compensate hysteresis and Feedback controller can be either PID or PI controller.
The vibration effect drastically limits the operating bandwidth and is often caused by the command signal exciting the flexible modes of the mechanical structure [42]. Higher operating speed can be achieved by using stiffer piezoelectric actuator with higher resonance frequency [130].

2.6.6 Feedforward Control Scheme

Even if feedback controllers have proved their performance in nanoscale positioning systems, challenging problems of nanoscale control remains due to non linear dynamics, actuators modeling uncertainties, instability and lack of robustness against external perturbations and sensor noise [143]. A variety of control techniques have been proposed to compensate the inherent nonlinearities of piezo actuators (PAs) and to improve precision and speed of nanopositioning systems using piezoelectric actuators. Feedforward controllers can be used to improve the output tracking performance of nanopositioning system such as SPM. Simple block diagram of nanopositioning device using feedforward controller is shown in figure 2.11.

![Simple feedforward control](image)
In this simplest form, feedforward controller $G^{-1}(s)$ is obtained by inverting the model of the plant, $G(s)$. The feedforward input to the system, $U_{ff}(s)$ is then given as

$$U_{ff}(s) = X_d G^{-1}(s)$$  \hspace{1cm} (2.2)

$$X(s) = U_{ff}(s).G(s) = X_d (s)$$  \hspace{1cm} (2.3)

Equation 2.2 indicates theoretically perfect tracking between the output, $X(s)$, and the reference, $X_d(s)$. Feedforward control can be used independently [144] or with feedback controller to improve the performance of the nanopositioning system without increasing the positioning noise [67].

**2.6.7 Integrated Feedback and Feedforward Control**

Feedforward controllers improve the system performance without incurring the stability problem associated with the feedback design [6]. But feedforward control is effective only if a very accurate model is used and it is not typically robust when disturbances are introduced. Moreover, feedforward controllers cannot correct tracking errors due to plant uncertainties, so it is necessary to use feedback controller in conjunction with feedforward controller to reduce error due to plant uncertainties in the inverse input [48]. To obtain advantages of both feedforward and feedback controllers and to undertake different aspects of the control issues with different controllers integrated feedforward and feedback control schemes can be used. Integrated feedback and feedforward controllers can be used in two ways

i) Double loop integrated feedback controller and feedforward control scheme.

ii) Single loop integrated feedback controller and feedforward control scheme.

iii) Integrated high gain feedback controller and feedforward control scheme.

**2.6.7.a Double Loop Integrated Feedback and Feedforward Control**

In double loop approach as shown in figure 2.12, the feedforward is augmented with feedback controller to compensate nonlinearities. The feedforward input is obtained by using the model based inversion of complete dynamics of piezo based system shown in figure. The feedforward and feedback controllers are used in separate loops...
of the control structure, and total control input \( u \) is produced by adding output of both feedforward \( U_{ff} \) and feedback \( U_{fb} \). With this configuration, if either component is shut off, the system will still be functional.

![Diagram of Double Loop Integrated Feedback with Feedforward Control](image)

**Figure 2.12** Double loop integrated feedback with feedforward control [6]

In this scheme, to achieve perfect tracking of the desired output signal, the feedforward controller input \( H^{-1}(G^{-1}r) \) must be the exact inverse of piezoelectric actuator based nanopositioner \( G'[H(v)] \). Low gain margin problem of nanopositioning system can be removed such that high frequency positioning performance can be improved over feedback controller [40,145]. Although the feedforward input obtained by using model based inversion improves the positioning precision, it is very difficult to invert dynamics of piezoelectric actuator which includes both the non linear effect and linear vibrational dynamics. Inversion of the linear vibrational dynamics is relatively simpler than the inversion of non-linear hysteresis with linear vibration effect [23].

### 2.6.7.6 Single Loop Integrated Feedback and Feedforward Control

This approach is used to reduce the modeling and computational complexity to inverse hysteresis with vibration effects. Here firstly, by using the feedback the system is linearized to overcome the hysteresis effect. Next the linearized closed loop system \( G_{cl} \) can be inverted to compute the feedforward input which is much simpler than to invert complete non-linear dynamics of the piezo based system. The generalized schematic of this approach is shown in figure 2.13.
In this single loop configuration, feedforward controller is the inverse linear dynamic of the closed loop system $G_{cl}$ and make the output $y$ to follow the desired input $r$. Feedback is used to reduce the uncertainty in the closed loop system $G_{cl}$, the feedback controller is a high gain feedback controller to suppress the non linear effect so that the closed loop system has linear dynamics. Thus the feedback is used to reduce the error in computing the feedforward input.

While in this scheme, the inversion of the closed loop linear dynamic of system is easy to compute, the achievable positioning bandwidth of the closed loop system $G_{cl}$ is limited. This scheme is sensitive to disturbances outside the closed loop system and low gain problem with the feedback loop is also exist [6,40].

2.6.7.c Integrated High Gain Feedback and Feedforward Control

S. Devasia et al. [68] experimentally shows that a high-gain feedback controller, a controller cascaded with notch filter, can be designed to compensate for errors caused by creep and hysteresis effects. Next, the performance of the feedback controller is further improved by adding feedforward input obtained through a model-based approach. Such an integration of feedback and feedforward does not limit the choices of the feedback approach, i.e., the model-based feedforward technique can be used with any of the existing or emerging feedback approaches [146]. The block diagram of this approach is shown in figure 2.14, where $U_{ff}$ and $U_{fb}$ are the output’s feedforward and feedback controller respectively.
Notch filter is used to improve the low gain margin of the system. Moreover, this integrated approach provides robustness to parameter variation and simplifies the computation of the feedforward input by avoiding the modeling of the creep and hysteresis behaviors. This approach using high gain feedback controller integrated with feedforward controller can also be applied for single loop scheme to improve the gain margin of the system.

2.6.8 Iterative Learning Control (ILC)

Feedforward control is commonly applied to improve the system’s tracking performance if the plant model is accurate. Linear time invariant (LTI) feedforward controllers suffer from robustness to plant dynamics uncertainty and in a system having significant change in resonance frequency, these controllers may not be viable [146].

In many applications of precise positioning, such as AFM scanning and probe based nano pattern generation, precise tracking of repeating (periodic) reference trajectory is needed. However, during positioning, the tracking error caused by the inherent nonlinearities such as hysteresis and dynamic effects, present in the piezoelectric actuators leads to significant positioning error [6,40]. Moreover, for repetitive operations, reference trajectory and disturbances are periodic or repetitive in nature, so tracking error repeats from one operating cycle to another and limits the performance of probe based nanopositioners. Under such conditions, Iterative Learning control (ILC) and adaptive control can be applied to improve the positioning performance of the system [147-148]. ILC can also be used even if the
scanning process is not repetitive [76]. In iterative learning control scheme, feedforward control signal can be generated by error signal produced by the successive period of a reference signal (iterative technique) for both dynamics and hysteresis compensation. Feedforward control signal invert the dynamic response of the system and cancel any deterministic disturbances. [149].

To design ILC, it is assumed that the system’s operating conditions remain same during each operation and the errors in the output response repeat during each operation. The objective is to make use of the information from previous operating trials to improve the response in the next iteration. Hence, in ILC performance of the system can be improved through repetition. The schematic of ILC is shown in figure 2.15. In this schematic, $y_d$ is the desired output, and $u_k$ and $y_k$ are the input and output at the $k^{th}$ iteration, respectively. Error $e_k$ is the difference between desired output and output of the system at $k^{th}$ iteration. Therefore, the objective to find an input $u_{k+1}$ for the next step i.e $k+1^{th}$ iteration, such that the performance of the system is better than the previous step.

![Figure 2.15 Schematics of ILC](image)

This control technique which is effective for reducing the hysteresis and dynamic effects in piezoelectric actuators has been applied to various nanopositioning systems and provide practically perfect reference tracking [76,147]. ILC method can be easily implemented with minimal system information. This is particularly important for piezo systems because the model can change over time due to aging effects. Furthermore, for additional improvement in positioning performance, ILC can be
augmented with the feedback control approach [149]. But it requires resetting of the initial conditions at the start of each iteration step.

2.6.9 Repetitive Control

Recently, for tracking periodic trajectories, a feedback based approach called Repetitive Control (RC) has been used to reduce tracking error from one cycle to the next in nanopositioning applications such as high speed and metrological AFM. RC is based on the internal model principle of the system where signal generator is incorporated into a feedback loop to create high gain at the fundamental frequency of the reference trajectory and its harmonics [6,150]. RC can be digitally implemented using a pure time delay inside a positive feedback loop. Therefore, RC is a feedback based approach well suited for tracking periodic reference trajectories and/or for rejecting periodic disturbances by exploiting the process of repetition. RC can be plugged into an existing feedback control scheme to improve system performance when reference trajectory is periodic in time.

Traditional PID controllers require careful tuning of its parameters and the residual tracking error persist for one signal period to the next whereas RC eliminates tracking error to zero as the number of cycles increases. The tracking error of RC decreases as the number of operating period increases. Compared to feedback and model based feedforward schemes, where accurate modeling of hysteresis and linear dynamics of the system are needed, RC require only the accurate knowledge of the period of the reference trajectory. Moreover, Unlike ILC, RC does not require resetting the initial conditions at the start of each iteration step. Since feedback mechanism in RC provides robustness, RC method is most suited for tracking periodic reference trajectories [50,151]. For nanopositioning system consisting of piezoelectric actuator, repetitive control can be designed for low tracking error in the presence of hysteresis and dynamic effects [150].

Advantages of this scheme include minimal system modeling, robustness due to the feedback structure and straightforward digital implementation [23] but this control scheme requires prior knowledge of the period of the reference trajectory.
2.6.10 Modern Control Schemes

In the feedback control system design, the main challenge is the performance improvement while maintaining the stability of the overall system in the presence of parameter uncertainties and unmodeled high frequency vibrational modes. Significant improvement in the precision and bandwidth of the nanopositioning system consisting of piezoelectric actuator can be achieved using advanced control techniques. These control techniques are state feedback [134], adaptive control and lead and lag method [152]. State feedback control schemes such as polynomial based (Pole Placement Control), constant gain feedback controller such as Linear Quadratic Regulator (LQR), Linear Quadratic Gaussian (LQG) regulator and Model reference control can also be used to improve system response characteristics especially for the systems having open loop unstable poles and non minimum phase zeros.

A successfully designed control system must be able to maintain stability margins and performance level even in the presence of uncertainties/ nonlinearities in system dynamics and/or in the working environment to a certain degree. To meet these requirements, even in the presence of non-linearities, modern model based control schemes for the output feedback in linear system such as robust controllers using the \( H_\infty \) synthesis can be used. \( H_\infty \) synthesis is the most practical framework for synthesizing robust controllers for linear systems as it guarantees a solution to the control design problem. Robust controller using \( H_\infty \) synthesis has been used in many nanopositioning applications and several results can be found in literature [36,41-42].

It is very difficult to model piezoelectric actuator dynamics because parameters such as applied voltage to induced strain and external loads are not known accurately. Therefore, development of a priori accurate model for controller design is a big challenge. Even when parameters are known, they change over long interval because of aging effects and temperature variations. Therefore, robust, adaptive and learning controls are well suited for the control of piezoelectric actuator based nanopositioning system.
2.7 CONCLUSION

Having described the components of nanopositioning system and various control methods in this chapter, the development of nanopositioning system’s dynamics in the form of system model would be the subject of the next chapter (Chapter 3) wherein modeling and analysis of a type of nanopositioning system have been detailed.