CHAPTER 7
CONCLUSIONS AND FUTURE SCOPE

This chapter highlights the summary and key findings of the research work. In this chapter, results obtained from the simulation of closed loop nanopositioning system using different types of controllers are summarized. This chapter concludes with the scope for future research work.

7.1 INTRODUCTION

Over the past two decades, an explosive growth in the field of nanotechnology has been observed. It has the potential to bring about the next industrial revolution for humankind. It is the technology to study and control of matter at the nanoscale i.e. dimensions between approximately 1 and 100 nanometers, where unique phenomenon enables novel applications. It involves imaging, measuring, modeling and manipulation of matter with nanoscale precision. The engineering research in nanotechnology is expected to lead the breakthrough in the area such as health care and medicine, advanced materials, electronics, manufacturing, biotechnology, defense etc. Nanopositioning is an important aspect of nanotechnology research which involves manipulation and precision control of matters and devices at nanoscale.

Nanopositioners are precise mechatronic systems designed not only to move or position a probe, part, tool, sample, or device at some desired position with nanometer accuracy and repeatability but also to resolve adjacent positions that are separated by less than a nanometer. The desired performance characteristics of a nanopositioner are precise positioning, long travel range, extremely high resolution, accuracy, wide bandwidth, stability, fast response with very small or no overshoot and robust closed loop position control.

The main issues for the nanoscale precision are to design and manipulate the positioning system with extremely high resolution, bandwidth, accuracy and stability. To achieve all these characteristics, a large number of
nanopositioning system geometries have been available. A nanopositioning system is an assembly of precise detection system, solid state smart actuators driven by the control systems and monolithic motion guide stage. In order to realize precise positioning at sub nanometer resolution, all these elements are to be carefully designed, analyzed and optimized. For highly accurate and high speed nanoscale positioning applications, recently, nanopositioning systems based on the piezoelectric stack actuators using flexure guided mechanism have been developed.

The performance analysis of control system focuses on time domain characteristics such as maximum overshoot, rise time, settling time and steady state error and frequency domain characteristics such as phase and gain margins. Inherent non-linearities and poor performance of open loop nanopositioning systems have motivated the researchers to improve the performance of nanopositioning system by using different controllers.

The dynamic characteristics of the piezoelectric based nanopositioning system have been analyzed by many research groups and found that open loop characteristics of the nanopositioning system are very poor, particularly it has very high value of settling time, maximum overshot and small value of phase margin. To achieve desired time and frequency domain performance specifications, various control techniques have been suggested in the literature survey. In this research work, different types of controllers are designed and implemented to achieve satisfactory system performance and good robustness and significant improvement in the system performance has been obtained.

7.2 CONCLUSIONS

In this section, the work done towards achieving the research objectives is presented. This thesis considers the key issues of nanopositioning in the field of nanotechnology and intended to address the major issues in the modeling and control of nanopositioning system. The main work done in this research includes the following:
• An extensive literature review has been conducted to understand the concept of nanotechnology, nanopositioning, dynamics of nanopositioning system and issues related to the modeling and control of nanopositioning system.

• Comprehensive study about the piezoelectric based flexure guided nanopositioning system has been done and its dynamic characteristics have been analyzed.

• In this work, a type of nanopositioning system has been selected and by obtaining its simplified model, dynamic characteristics have been analyzed. It has been found that the selected system was 4\text{th} order, linear and non minimum phase for which the open loop performance characteristics were: high value of settling time, very high value of overshoot and low values of phase and gain margins.

• Various existing control schemes have been studied and implemented on the selected nanopositioning system. Work has been done towards improvement and modifications and overall system performance enhancement has been achieved.

The contributions of this research work are to explore the implementation of the conventional and modern controllers to the nanopositioning system and investigate the performance analysis. Further, the tuning of the controller parameters, pole locations and choice of weighting matrices had been proposed which resulted in performance improvement of the nanopositioning system. The highlights of the work done are given below:

➢ Conventional controllers such as P, PI, PID and PII controllers have been designed and tuned using different tuning algorithm. By using conventional controllers, improvement in the system performance has been achieved.

➢ In order to obtain efficient set point tracking and output disturbance rejection, IMC controller has been designed and implemented. Significant improvement in the time response characteristics has been obtained.

➢ To place closed loop poles arbitrarily at the desired location, pole placement controller using state space technique has been implemented on the nanopositioning system and further improvement in the system performance
has been observed. By adding a constant gain after the reference input to the system, reduction in the steady state error and improvement in performance characteristics of the system has been achieved.

- A state observer has been designed and significant improvement in the system performance has been obtained by using observer based pole placement regulator.

- To obtain optimal control, linear quadratic controller (LQR) has been designed and implemented for the nanopositioning system which not only places the poles at arbitrary location but also guaranteed stable closed loop poles with more desirable robustness. Values of state weighting matrix, Q, and cost control matrix, R, has been selected to improve the system performance. To reduce steady state error, a constant gain after the reference input has been added and substantial improvement in performance characteristics of the system has been achieved.

- Every plant has some uncertainties and system performance degrades accordingly. System performance improvement and robustness against system uncertainties have been obtained by designing and application of robust controllers for the selected nanopositioning system.

- A comparative analysis of different types of controller on the basis time and frequency response characteristics has been done and it has been concluded that different type of controller works well for different conditions and applications. The simulated results are obtained in MATLAB environment.

The comprehensive results for transient response characteristics for conventional controllers, state feedback controllers and robust controllers are shown in figure 7.1 for performance comparison.
The time response and frequency response characteristics of the closed loop nanopositioning system using different types of controllers are tabulated in table 7.1. As depicted from table 7.1, the time and frequency response characteristics of the nanopositioning system for open loop configuration are not satisfactory. So, to improve system performance, different types of controllers have been designed.
<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Rise time (sec.)</th>
<th>Settling time (sec.)</th>
<th>$M_p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open loop</td>
<td>0.0066</td>
<td>0.0335</td>
<td>83.061</td>
</tr>
<tr>
<td>Proportional Controller</td>
<td>0.00659</td>
<td>0.0335</td>
<td>83.61</td>
</tr>
<tr>
<td>PI Controller</td>
<td>0.0300</td>
<td>0.0549</td>
<td>0</td>
</tr>
<tr>
<td>IMC</td>
<td>0.00577</td>
<td>0.0102</td>
<td>0.009</td>
</tr>
<tr>
<td>Pole placement regulator</td>
<td>0.00478</td>
<td>0.00778</td>
<td>0.902</td>
</tr>
<tr>
<td>Linear Quadratic Regulator</td>
<td>0.000391</td>
<td>0.00174</td>
<td>11.95</td>
</tr>
<tr>
<td>$H_2$ Controller</td>
<td>0.0161</td>
<td>0.022</td>
<td>0</td>
</tr>
<tr>
<td>Suboptimal $H_\infty$ Controller</td>
<td>0.00089</td>
<td>0.00424</td>
<td>9.86</td>
</tr>
<tr>
<td>$H_\infty$ Optimal Controller</td>
<td>0.00090</td>
<td>0.00424</td>
<td>9.86</td>
</tr>
</tbody>
</table>

Table 7.1 Performance characteristics of the nanopositioning system for different types of controllers

As observed from the table 7.1, proportional controller hardly improves the performance characteristics of the closed loop system. The complete elimination of maximum overshoot of open loop system has been achieved by PI controller at the cost of increase in settling time. Set point tracking, disturbance rejection and improvement in system performance have been achieved by using IMC. Stability and time response characteristics of the system have been further enhanced by using modern state space controller.

Closed loop response of nanopositioning system using Pole placement regulator has shown that system performance can be improved by moving closed loop poles deeply into the left half plane. By adding a constant gain after the
reference input to the system, improvement in performance characteristics of the system has been obtained.

Using optimal LQR, effective performance of the system for different values of the performance index matrices Q and R has also been analyzed and a conclusion has been drawn that an increase in weighting matrix Q results in decline in the settling and rise time of the system which makes system speedy and stable. Stability margins and bandwidth are also improved by increasing Q. Decrease in the R causes the increases in the maximum feedback gain and decrease in the required control input. This results an enhancement in the time response and frequency response characteristics of the system. The correlation between Q and R concludes that system performances can be improved by increasing the weight of Q and decreasing the weight of R matrices.

Simultaneous requirement of both system performance and robustness against model uncertainties have been achieved using robust controllers. It has been observed that overshoot has been drastically reduced by using robust controller. Remarkable improvement in stability margins and transient response characteristics i.e rise time and settling has been observed by the implementation of robust controllers on the nanopositioning system. The results demonstrate a substantial improvement in the performance of nanopositioning system.

7.3 SCOPE FOR FUTURE WORK

In the present research work, different types of controllers have been implemented on the selected nanopositioning system. Though PID controllers for considered nanopositioning system had been tuned using standard algorithm but desired characteristics of the nanopositioning system were achieved by tuning controllers’ parameters using trial and error method. Similarly, state space and robust controllers were also tuned via trial and error method which was quite time consuming. Moreover, in this research work non-linearities of the nanopositioning system were not considered. So, the following aspects may be considered for the future scope of the present research work.
- Modeling of nanopositioning system including inherent non linearities
- Non-linear control of nanopositioning system
- Real time application of nanopositioning system
- Multi axis nanopositioning system
- Application of intelligent control schemes for performance improvement of nanopositioning system