# Chapter 7

# Conclusions

## 7.1 Introduction

The aim of the work was to develop robust controllers using sliding mode approach for accurate control for single link and two link flexible manipulators with minimum tip vibrations. For these model based controllers, accurate models have been developed accounting the flexibility of the FLM. To capture better dynamics, a novel fractional order model of SLFM is proposed. For this fractional model, control and estimation scheme has been designed for the control of an underactuated SLFM system. More accurate model for 2LFM has also been developed based on AMM approach.

Robust controllers have been studied for SLFM and 2LFM using basic SMC approach. These controllers proved to be robust against external disturbances and model uncertainties. However their performance showed certain limitations such as chattering in the input and it required the complete state vector for implementing the control law. Therefore state estimators have been designed. Also to implement the controllers without the need of the estimators, output feedback controllers have been investigated for SLFM and 2LFM.

## 7.2 Concluding remarks

- Control of the SFLM and 2LFM using sliding modes have been investigated. TA and STA based controllers have been developed for control of FLM. The system has been analyzed with parametric variations and matched disturbance. Although chatter has been observed in control input. HOSMC outperforms SMC with respect to control efforts. The norm 2 of the control input using HOSM shows substantial reduction with respect to SMC. It is reduced by approximately $50\%$ in TA scheme and by $60\%$ in STA scheme.

- Sliding mode controller synthesizing fractional surface has been investigated. Fractional model of SLFM has been found to be more accurate than integer model. It is observed that the modeling errors were reduced by $44\%$ compared to integer order model.

- Fractional sliding mode control has been devised using estimated states through FSMO. With this scheme, the vibrations of SLFM are suppressed while tracking the desired position. It also yields smooth control input. It is observed from the experimental results that FSMC with FSMO requires $32\%$ less control efforts compared with integer SMC with SMO scheme while achieving same performance specifications in terms of settling time.

- When HOSMC is complimented with DO for the control of 2LFM, substantial reduction in the control effort of around $12\%$ has been observed. It proves that using accurate estimation of the disturbances, control can be optimized.

- In output feedback controller for 2LFM, TA based controller provides finite-time convergence of the output and its first derivative. However it produces discontinuous control. Continuous TA based controller generalizes the twisting algorithm with continuous control.

All the proposed methods have been validated via extensive simulations and experiments.
The thesis demonstrates robust, simple and implementable control methods for control of FLM.

## 7.3 Future Work

The problem of the control of flexible link manipulator using sliding modes has been attempted successfully. The following suggests the directives for the future work.

- Proposed methods can be extended for multi link manipulators with more degrees of freedom.
- Joint trajectory tracking with minimum vibrations is achieved. The technique can be extended to end effector trajectory tracking of the FLM.
- New methods of modeling can be investigated e.g. image processing tool to devise exact number of nodes in real time to get better model. Image processing tool can also be investigated for designing necessary control.