

# List of Figures

2.1	Schematic diagram of flexible link . . . . .	17
2.2	DC Motor: Equivalent circuit . . . . .	20
2.3	Plant of SLFM system . . . . .	22
2.4	Experimental set up of single flexible link . . . . .	23
2.5	A planar two-link flexible manipulator . . . . .	25
2.6	Plant of TLFM system . . . . .	28
2.7	Block diagram . . . . .	29
2.8	Experimental Setup of TLFM system . . . . .	30
2.9	A schematic of two-link flexible manipulator . . . . .	32
2.10	Pulse input . . . . .	42
2.11	Response to pulse input . . . . .	42
2.12	Square wave input . . . . .	43
2.13	Response to square wave input . . . . .	43
3.1	Vector field of Twisting Controller . . . . .	51
3.2	Twisting Trajectory . . . . .	52

3.3	Super-twisting algorithm phase trajectory . . . . .	54
3.4	Evolution of Angular Displacement . . . . .	59
3.5	Evolution of Angular Velocity . . . . .	59
3.6	Evolution of link's tip displacement . . . . .	60
3.7	Rate of change of tip displacement vs time . . . . .	60
3.8	Control Input . . . . .	61
3.9	Evolution of Angular Displacement . . . . .	62
3.10	Evolution of Angular Velocity . . . . .	62
3.11	Evolution of link's tip displacement . . . . .	63
3.12	Rate of change of tip displacement vs time . . . . .	63
3.13	Control Input . . . . .	64
4.1	Block diagram of FOPID controller for SLFM plant . . . . .	73
4.2	Output response of FOPID and IOPID . . . . .	74
4.3	Fractional order PID . . . . .	75
4.4	Plot of output angular displacement verses time . . . . .	80
4.5	Plot of variation of angular velocity . . . . .	80
4.6	Plot of tip displacement verses time . . . . .	81
4.7	Rate of change of tip displacement . . . . .	81
4.8	Evolution of sliding surface . . . . .	81
4.9	Control efforts . . . . .	82
4.10	Output angular displacement verses time . . . . .	83

4.11	Plot of variation of angular velocity . . . . .	83
4.12	Plot of tip displacement verses time . . . . .	83
4.13	Rate of change of tip displacement . . . . .	84
4.14	Evolution of sliding surface . . . . .	84
4.15	Control efforts . . . . .	84
5.1	Tip deflection for simulation models (FO and IO) and for actual plant . . . . .	98
5.2	Modeling errors . . . . .	98
5.3	SMO: Estimation error in $\theta$ and $\dot{\theta}$ . . . . .	102
5.4	SMO: Estimation error in $\alpha$ and $\dot{\alpha}$ . . . . .	102
5.5	FSMO: Estimation error in $\theta$ and $\dot{\theta}$ . . . . .	103
5.6	FSMO: Estimation error in $\alpha$ and $\dot{\alpha}$ . . . . .	103
5.7	Angular displacement and its rate of change . . . . .	104
5.8	Tip displacement and its rate of change . . . . .	105
5.9	Control input . . . . .	105
5.10	SMO: Estimation error in $\theta$ . . . . .	106
5.11	SMO: Estimation error in $\alpha$ . . . . .	107
5.12	FSMO: Estimation error in $\theta$ . . . . .	107
5.13	FSMO: Estimation error in $\alpha$ . . . . .	107
5.14	Evolution of output angular displacement and its rate . . . . .	108
5.15	Evolution of angular tip displacement and its rate . . . . .	109
5.16	Control Input . . . . .	109

6.1	Closed loop response of a shoulder motor to step command . . . . .	118
6.2	Evolution of angular velocity of shoulder system . . . . .	118
6.3	Plot of control input to shoulder system . . . . .	118
6.4	Actual and estimated disturbance for shoulder joint . . . . .	119
6.5	Closed loop response of an elbow system . . . . .	119
6.6	Evolution of angular velocity of elbow system . . . . .	120
6.7	Plot of control input to elbow system . . . . .	120
6.8	Actual and estimated disturbance for elbow system . . . . .	120
6.9	Evolution of motor deflection angle $\theta_1$ . . . . .	126
6.10	Evolution of motor deflection angle $\theta_2$ . . . . .	126
6.11	Control Effort $\tau_1$ . . . . .	127
6.12	Control Effort $\tau_2$ . . . . .	127
6.13	Evolution of flexible modes of the first link . . . . .	128
6.14	Evolution of flexible modes of the second link . . . . .	128
6.15	Evolution of motor deflection angle $\theta_1$ . . . . .	129
6.16	Evolution of motor deflection angle $\theta_2$ . . . . .	130
6.17	Control Effort $\tau_1$ . . . . .	130
6.18	Control Effort $\tau_2$ . . . . .	130
6.19	Tip deflection of link 1 measured by strain gauge . . . . .	131
6.20	Tip deflection of link 2 measured by strain gauge . . . . .	131
6.21	Evolution of motor deflection angle $\theta_1$ . . . . .	134

6.22	Plot of control Input $u_1$ verses time . . . . .	134
6.23	Evolution of motor deflection angle $\theta_2$ . . . . .	135
6.24	Plot of control Input $u_2$ verses time . . . . .	135