

Table of Contents

Table of Content	i
Abstract	viii
1. Introduction	1
2. Modeling	7
2.1. Friction Model	7
2.2. The Overall Joint Model	11
2.2.1. Gear Efficiency	12
2.2.2. Bearing Friction Calculation	18
2.3. Link Reactions	31
2.4. Backlash Model	37
2.4.1. Solution of Dynamic Equations of Motion	41
2.4.2. Friction Calculations	44
2.4.3. Calculation of Reactions	48
2.5. Modified Newton-Euler Recursive Relations	54
2.6. Actuator Model	63
3. Simulation Studies	70
3.1. An Efficient Method for Dynamic Computation	70
3.2. Trajectory Development	81
3.2.1. Polynomial Fitting	82
3.2.2. Segment Length Considerations	89
3.2.3. Joint Interpolated Motion (The Algorithm)	90
3.2.4. Motion Between Two General Positions	91
3.2.5. Differentials Calculation of T_6	94
3.2.6. End Effector to Joint Differential Transformations	98
3.2.7. Joint to End Effector Differential Transformations	103
3.2.8. Computer Model	116
4. Design Considerations	130
4.1. Computational Efficiency	130
4.2. Link Reaction Minimization	145
4.3. Design for Minimum Friction	155
4.4. Specification of Friction Limits	160
4.5. Specification of Backlash Limits	166
5. Control Methods	181
5.1. Least Squares Adaptive Control (LSAC)	182
5.2. Trajectory-Update Joint Control (TUJC)	195
5.2.1. Trajectory-Updating	196

5.3. Resolved Trajectory-Update Control (RTUC)	200
5.4. Backlash Based Control (BBC)	201
6. Summary and Conclusions	205
6.1. Results and Discussion	205
6.2. Future Work	218
References	254
Appendix A. Joints, Links, and Coordinates	256
Appendix B. Newton-Euler Recursive Relations	259
Appendix C. Differentiation of T_6	263
Appendix D. Equivalent Angle and Axis of Rotation	266
Appendix E. Forward and Backward Solution of Stanford Arm	268
Appendix F. Composite Proof	276
Appendix G. Reaction Simplifications	280
Appendix H. Segment of Transition	283
Appendix I. L.S.A.C Recursive Relations	287
I.1. Partial Derivatives With Respect to q	287
I.2. Partial Derivatives With Respect to Speed	294
I.3. Partial Derivatives of the Driving System With Friction	300
I.3.1. Partial Derivatives of Friction Torques	304
I.3.2. Partial Derivatives of Translational Link	314
I.4. The General Form of the Partial Derivatives	315
Appendix J. Computer Program	322