DEVELOPMENT OF HIGH BANDWIDTH TORQUE SENSOR FOR CONTROL OF HIGH PERFORMANCE MANIPULATORS

A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
ENGINEER

Sanford Miles Dickert

March 1999

Approved for the Department:

Advisor

Approved for the Committee on
Graduate Studies:

Advisor

Abstract

In advanced manufacturing environments, the current state-of-the-art in robotic manipulators focuses primarily on improving the performance of position-based control through advanced vision systems and improved motor-amplifier technology. The fundamental issue of actuator position control has been left to motor amplifier designers to incorporate steady improvements on sensor and commutation methods. However, in all robotic control efforts, control of the link torque is paramount and it is here where design efforts should be applied to develop a new actuator position control scheme.

The ARTISAN manipulator, a high-performance torque-controlled, eleven degree-of-freedom manipulator and mini-manipulator system under construction at Stanford University, attempts to address the issue of fine actuator control by incorporating in its design a link torque control loop. By applying a fast link torque loop to the actuator, position control of the end effector is improved. The ARTISAN manipulator requires a high-performance, high bandwidth torque sensor in order for the link torque control loop to be successful.

This thesis focuses on the development of the high-bandwidth torque sensor. It covers the design of the sensor, transducer and converter selection, and compensation design. In addition, the physical components of the ARTISAN wrist joint are identified, and together with the new torque sensor, are simulated using SIMULINK. Finally, a control algorithm is designed and simulated to demonstrate the improved performance versus the open loop system. Future direction and recommendations for continued efforts are also presented.

For my Dad, "the Lazy Lion"

"It is not the critic who counts, not the man who points out how the strong man stumbled, or where the doer of deeds could have done them better. The credit belongs to the man who is actually in the arena; whose face is marred by dust and sweat and blood; who strives valiantly; who errs and comes up short again and again; who knows the great enthusiasms, the great devotions; who spends himself in a worthy cause; who, at the best, knows in the end the triumph of high achievement, and who, at the worst, if he fails, at least fails while daring greatly; so that his place shall never be with those cold and timid souls who know neither victory nor defeat."

- Theodore Roosevelt

Acknowledgements

As any Hollywood screenwriter knows, every story has a prologue, three acts, and an epilogue. Many years ago, I began at Stanford, fresh from four years of Purdue, looking forward to my pursuit of higher learning here at Stanford. It was in those first few weeks that I met Professor Gene F. Franklin. After becoming my academic advisor, Gene has been an instrumental force in my pursuit of academic excellence. Through my classes, research, sabbaticals and distractions, Gene has been there to help me through it all and has given me something to be proud of. For this guidance and support, I owe Gene a debt of thanks.

In my first act, where I pursued my Masters degree, there were a cast of characters who helped me through my first few years at Stanford - whether through monetary support, academic guidance or comradeship in the midst of midterms and final exams. Mrs. Marianne Marx is the person who supported me over the years through twenty-odd teaching assistantships in the EE department. She has been there from the beginning and gave me the opportunity to be the best teacher I could be - even when the evaluations were down. I owe her a tremendous debt of thanks for all she gave to me over the years. Ed Dillard and I started out at Stanford the same year, learning the ropes of ERL and all the job

entailed. Even after my teaching responsibilities gave way to research for this thesis, he has been a helpful friend to me. I also owe a thanks to Professor-Emeritus Malcolm MacWhorter, who was my teaching guide in my first few years; our many talks made a tremendous difference in my experience here at Stanford. And then there were my peers, Jill Gunderson and Kurt Zimmerman who were there through the good times and bad. I truly appreciated the friendship they provided over the years. It was during this time that I also met my friends in control theory - Dr. Vincent (VK) Jones and Dr. Geoffrey Chase. Both VK and Geoff have been invaluable over the years through the friendship and advice they have given to me.

In my second act, I continued my teaching and began work in the Computer Science Robotics Laboratory. It was there that I worked with Professor Oussama Khatib, who provided me with the puzzle of the ARTISAN link torque loop - a puzzle which is the crux of this thesis.   While there, I worked with some incredibe people - Oscar Madrigal, Alain Paccard, Alain Fidani, Alain Courdourney, Dr. David Williams, Dr. Sean Quinlan - and I owe a special thanks to Robert Holmberg, my partner-in-crime in the ARTISAN project. Where I played the brains (electrical engineer), he was the brawn (mechanical engineer). Bob is a terrific designer and will be a fantastic doctorate when he finishes. Additionally, I thank my friend Matthew Finnie, the original marketing engineer for the LVDT Converter components. He did his best in the bureaucracy that is Analog Devices and found research funds to test and create the sensor electronics boards that became the ARTISAN torque sensor.

For the third act, I must thank Paul Brokaw from Analog Devices and his furry friend, Mr. Big. Paul gave generously of his time when I returned to Stanford to finish my degree - my gift to him is the Appendices that make up this work. I also owe Richard Powers, instructor in the Stanford Dance Division, a thanks for the time, caring and friendship he has shown me over the years. He, through dance, has taught me more about creativity and expression than anyone else has over the years. And then there is Rolando Zeledon, one of the first students I taught

at Stanford in Introduction to Electrical Engineering. From the earthquake to today, Roli has been a true friend over all these long years. For his friendship and support, I thank him as well. I also must thank my editor of this thesis, Elise Lipkowitz and my roommate, Joe Kahn. Elise has been instrumental in making this thesis more "fuzzy-friendly" and cleaner while Joe has been a rock of support over the period of my third act. To them I extend thanks as well.

And finally, for my epilogue, I thank my family. Mom, Andrew and Blair have been a constant support through the years and they share in my triumph. But most of all I thank my father, Lawrence Dickert, for supporting me and caring for me over the years. Though he is not here today to share in this moment - the moment is his nonetheless.

Table of Contents

List of Tables

List of Figures