

Fast Perception-Action Loops with Proximity Sensors for Robotic Manipulators

Band 3

Yitao Ding





TECHNISCHE UNIVERSITÄT
CHEMNITZ

Fast Perception-Action Loops with Proximity Sensors for Robotic Manipulators

Von der Fakultät für Elektrotechnik und Informationstechnik
der Technischen Universität Chemnitz

genehmigte

Dissertation

zur Erlangung des akademischen Grades

Doktoringenieur

(Dr.-Ing.)

vorgelegt von

Yitao Ding, M.Sc.

Gutachter: Prof. Dr.-Ing. Ulrike Thomas
Prof. Kaspar Althoefer

Tag der Einreichung: 25.10.2021
Tag der Verteidigung: 03.06.2019

Fortschritte der Robotik/Progress in Robotics

Band 3

Yitao Ding

**Fast Perception-Action Loops
with Proximity Sensors
for Robotic Manipulators**

D 93 (Diss. TU Chemnitz)

Shaker Verlag
Düren 2022

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Chemnitz, Techn. Univ., Diss., 2022

Copyright Shaker Verlag 2022

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-8762-8

ISSN 2627-2482

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: www.shaker.de • e-mail: info@shaker.de

ABSTRACT

Proximity sensors attached to the outer shell of robotic manipulators provide fast and occlusion-free perception capabilities of the robot's nearby environment. They offer a solution towards fenceless collaborative workspaces by closing the gap in perception between (3D depth) cameras and tactile/force sensing. The perception gap occurs at the robot's close range, where external cameras provide insufficient information due to noise, resolution, and occlusion, and where tactile sensors remain untriggered. This thesis examines the fast perception-action loop of such systems to increase safety with reactive obstacle and collision avoidance motions and proactive adaption for impact attenuation. The loop consists of three elements: proximity perception, reactive motion generation, and the proactive adaption of the robot parameters.

The first part of the safety chain shows an on-robot proximity perception system. The concept behind the system is to combine two sensors. Laser-based time-of-flight sensing is used for far-range while capacitive proximity detection covers the blind areas by wide-area detection. A novel custom-designed capacitive proximity sensor is presented that is robust against different grounding conditions of obstacles, a significant issue of conventional capacitive proximity sensors. The perception system has characteristic features by providing rich near-field information with a limited quantity of measurement points, minimizing the amount of redundant information, and thus increasing responsiveness.

Reactive motions require only a few data points for fast motion generation and benefit from these features, especially for collision avoidance, where instantaneous adjustments of the robot's trajectory are mandatory. This thesis proposes two methods, one based on finding an avoidance vector with sampling in orthogonal directions towards the obstacle and another one by extending quadratic optimization to integrate the avoidance task within optimization constraints. Compared to common repulsive motions for collision avoidance, the proposed motion generators are less restrictive. They make full use of the robot's redundancy for task retention and provide solutions for multi-obstacle whole-arm obstacle avoidance. The algorithms further focus on evasive motions to bypass obstacles to decrease the risk of the robot freezing problem appearing. A phenomenon in which the robot gets stuck in local minima where it stops before obstacles in an equilibrium state of attraction towards the goal and repulsion from the obstacle.

The third part addresses the issue that collisions cannot always be prevented because the required avoidance motion exceeds the robot's motion capabilities. The last safety layer relies on the anticipation of contacts with proximity sensors to enhance the effectiveness impedance controllers for impact attenuation. The first measure modulates the stiffness of the impedance controllers as required, allowing faster, more accurate motions during regular operation while maintaining safety. A high stiffness setup suppresses positional disturbances during regular operation of the robot for high accuracy. The stiffness decreases only before impacts with safety as highest priority. The second measure slightly modifies the joint configuration to decrease the effective inertia of the manipulator at the impact point.

Keywords: *Proximity Servoing, Proximity Perception, Capacitive Proximity Sensors, Reactive Motions, Obstacle Avoidance, Collision Avoidance, Impact Attenuation*

For my family and friends.

CONTENTS

Abstract	iii
I Introduction	1
1 Background and Motivation	3
1.1 Background	3
1.2 Bridging the Perception Gap	5
1.3 On-Robot Proximity Perception	8
1.4 Overview of On-Robot Proximity Perception Applications	10
1.5 Closing the Servoing Loop with Reactive Motions and Actions	11
1.6 Main Contributions and Aim of the Thesis	13
2 Basic Knowledge and Related Research	17
2.1 On-Robot Proximity Perception: Artificial Skins	17
2.1.1 Sensing Modalities	18
2.1.2 Capacitive Proximity Sensing	22
2.1.2.1 Capacitance Measurement	22
2.1.2.2 Capacitive Proximity Sensing Topologies	24
2.1.2.3 Inferring Proximity from Capacitance	25
2.1.3 Overview of On-Robot Proximity Sensing Systems	27
2.2 Reactive Motions	34
2.2.1 Inverse Differential Kinematics	34
2.2.2 Task Priorities	38
2.2.3 Solving IDK with Constrained Optimization	39
2.2.4 Overview on Reactive Motion Generation with On-Robot Proximity Perception	42
2.3 Impact Attenuation	45
2.3.1 Impedance Controllers	46

2.3.2	Overview of Non-Mechanical Impact Attenuation Methods	48
II	Proximity Perception	51
3	Architecture of the On-Robot Proximity Perception System	53
3.1	Concept	53
3.1.1	Dual Modality Proximity Sensing Module	54
3.2	Mechanical Design	56
3.3	Communication	57
3.3.1	Inter-Sensor Communication	60
3.4	Proximity Data Processing and Self-Measurement Removal	64
3.4.1	Point Cloud Generation and Classification	65
3.4.2	Point Cloud Buffer	70
4	Capacitive Proximity Sensing	73
4.1	Design Considerations	73
4.1.1	Main Objectives	73
4.1.2	Sensitivity and Range	75
4.1.3	Detection Robustness and EMI Suppression	78
4.1.4	Noise Suppression and Final Sensing Circuit Design	79
4.1.5	Signal Processing	81
4.2	Evaluation	84
4.2.1	Detection of Differently Grounded Objects	84
4.2.2	Detection Volume	85
4.2.3	Range Uncertainty	88
4.3	Conclusion	88
III	Proximity Servoed Reactive Motions for Collision Avoidance	91
5	Real-Time Control System	95
5.1	System Overview	95
5.2	Real-Time Robot Control Interface	96
6	Sampling-Based Methods for Dynamic Collision Avoidance	101
6.1	Concept	101
6.2	Task-Priority Definition in Task Space	103
6.3	Avoidance Vector Sampling	105

6.4	Repulsive Motion Integration	106
6.5	Quality Scores	107
6.6	Evaluation and Discussion	110
7	Constrained Quadratic Optimization for Dynamic Obstacle Avoidance	119
7.1	Concept	119
7.2	Quadratic Program and Constraint Definition	119
7.2.1	Objective Function	120
7.2.2	Joint Constraints	121
7.2.3	Collision Avoidance Constraints	125
7.2.4	Collision Avoidance Constraint Parameter Configuration	126
7.2.5	Constraint Satisfaction Through Priority Definition	127
7.3	Evaluation and Conclusion	128
IV	Proximity Servoed Reactive Actions for Impact Attenuation	135
8	Variable Impedance Control for Impact Attenuation	139
8.1	Concept	141
8.2	Stiffness Control	142
8.3	Stability	144
8.4	Energy-Tank-Based Stiffness Control	146
8.5	Evaluation and Conclusion	148
9	Improving the Attenuation Effectiveness of Impedance Controllers by Joint Reconfiguration	153
9.1	Concept	154
9.2	Joint Reconfiguration	156
9.2.1	Manipulability Approach	156
9.2.2	Inertia Matrix Approach	157
9.2.3	Quadratic Program Integration	158
9.2.4	Collision on any Link	159
9.3	Evaluation and Conclusion	160

V	Summary and Outlook	165
10	Summary and Outlook	167
10.1	Summary of the Results	167
10.1.1	Perception	167
10.1.2	Obstacle and Collision Avoidance	168
10.1.3	Impact Attenuation	169
10.2	Outlook	170
10.2.1	Outlook for the Existing System	170
10.2.2	Outlook for Potential Applications	172
	Bibliography	175
	Appendix	187
A	Inverse Matrix Notation	187
B	Sensor Schematics	190
	List of Figures	193