Robust Active Compliance Control for a Robot Hand

University of BRISTOL

Jamaludin Jalani

A dissertation submitted to the University of Bristol in accordance with the requirements for award of degree of Doctor of Philosophy in the Faculty of Engineering

March 2013

Word Count : 36,000

Abstract

This project deals with safety issues in human-robot interaction. A particular focus of this project is on a humanoid robot hand which requires (physical) safety to interact with objects/humans. A robust and active compliance control is proposed via an Integral Sliding Mode Controller (ISMC) to achieve safe object grasping. The ISMC allows us to introduce a model reference approach where a virtual mass-spring damper system can be used to design a compliant control.

The first stage of the studies requires the derivation of the forward kinematics for the Bristol Elumotion Robot Hand (BERUL) by using the DH technique. With the help of the motion and image capturing tool, Roborealm, the kinematics data of the robot hand are obtained to compute the relationships between the joint angles. The forward kinematics results show that a suitable model for a single robot finger can be represented via a pulley-belt type system.

The second stage requires the investigation of the ISMC for tracking and positioning control. The results reveal that the ISMC is the most suitable candidate for tracking and positioning control in particular to eliminate friction and stiction, also in comparison to standard PID, adaptive and traditional sliding mode control.

The third stage of the PhD-research introduces a novel model reference approach for active compliance control via the ISMC in simulation and experiment. The ISMC provides a non scheduled compliant control where transition from positioning to force control can be eliminated. It is practically proven that the BERUL fingers can perform at different, specially designed compliance levels for specific objects. Further improvement for practical grasping is proposed by introducing a spherical coordinate system for the thumb finger and exploiting a cylindrical coordinate system for the other remaining fingers. The operational space control approach is proposed to permit finger (i.e. hand) posture optimization for practical grasping; this also reduces the need for high accuracy.

Finally, an automatic tuning procedure is introduced for the compliance reference model which will allow to find suitable compliance level parameters for specific objects.

Contents

Contents vi

List of Figures xi

List of Tables xiv

List of Abbreviations xvi

List of Symbols xvii

1 Introduction **1**

1.1 Background 1

1.1.1 General 1

1.1.2 Project Context 2

1.2 Problem Statement and Objectives 5

1.3 Methodology 6

1.3.1 Compliant Control Strategy 7

1.4 Outline of the Thesis 8

2 Literature Review **11**

2.1 Compliance Control 12

2.1.1 Passive Compliance Control 15

2.1.2 Recent Developments in the Area of Passive Compliance 17

2.1.3 Active Compliance Control 18

2.1.4 Hybrid Active/Passive Compliance Control 20

2.1.5 Compliance Level 20

2.2 Hand Grasping 21
2.3 Underactuated Robot Hand and Fingers 26
2.4 Modelling 28
2.4.1 Kinematics 28
2.4.2 Dynamics Modelling of Robot Hand 33
2.4.3 Friction and Stiction 36
2.4.4 Modelling the Contact 36
2.5 Sensors 38
2.6 Position Control and Force Control 40
2.7 Operational Space Control 41
2.7.1 Kinematic Redundancy 41
2.7.2 Posture Controller 43
2.8 Integral Sliding Mode Control 46
2.8.1 Conventional Sliding Mode Control 47
2.8.2 An Integral Sliding Mode Control 52
2.8.2.1 Example via robot manipulators control 54
2.9 Summary 59

3 The BERUL-Hand: Kinematics and Dynamics, Experimental Set Up 61
3.1 Introduction 61
3.1.1 The BERUL Fingers 61
3.2 Forward Kinematics 63
3.2.1 Roborealm 63
3.2.1.1 Roborealm: The Capturing Process 64
3.2.2 DH Representation 72
3.2.3 Kinematics Results 74
3.3 Dynamic Analysis 77
3.3.1 Dynamic Analysis of the Underactuated Finger 77
3.3.2 MapleSim 81
3.3.3 SimMechanics 82
3.4 Experimental Setup 84
3.4.1 The BERUL hand: Actuator and Bus Communication 86
3.4.2 MATLAB/Simulink and dSPACE 86

3.4.2.1 Analog to Digital Converter (ADC) 87
3.4.2.2 S-functions 87
3.4.3 SPTS sensor 88
3.4.4 EPOS Firmware Interface 89
3.4.4.1 Built-In PID 91
3.4.4.2 CAN and CANopen 91
3.4.5 Safety Button 92
3.5 Summary 92

4 Underactuated Fingers Controlled by Robust and Adaptive Trajectory Following Methods 93
4.1 Introduction 93
4.2 Controller design strategies 94
4.2.1 Adaptive Controller 94
4.2.2 PID Controller 96
4.2.3 Conventional Sliding Mode Controller (SMC) 97
4.2.4 Integral Sliding Mode Controller (ISMC) 98
4.2.5 Implementation 98
4.3 Results and Performance 99
4.3.1 Quantitative Measure of Controller Performance 99
4.3.2 PID Tuning, Performance and Results 101
4.3.3 Adaptive Control Tuning, Performance and Results 102
4.3.4 Conventional Sliding Mode Control Tuning, Performance and Results 104
4.3.5 Integral Sliding Mode Control Tuning, Performance and Results . . 105
4.3.6 Chattering Reduction 107
4.3.7 Comparative Analysis 109
4.3.8 Results for other fingers (index, middle, ring and small) 110
4.4 Discussion 111
4.5 Summary 112

5 A Novel Approach of Robust Active Compliance Control for Robot Fingers 113
5.1 Introduction 113
5.2 Controller Design 113

5.2.1 Integral Sliding Mode Controller (ISMC) 114
5.2.2 Compliance 115
5.2.3 Computation of Compliance Levels 116
5.3 Results 117
5.3.1 Compliance Model Design For Simulation 117
5.3.2 Simulation: Preliminary Results for Compliance 117
5.3.3 Simulation: Compliance Level for Different Stiffness 120
5.3.4 Compliance Model Design For Experiment 124
5.3.5 Experiment: Compliance Level for Different Stiffness 124
5.3.6 Experiment: Results for Grasping Objects 129
5.4 Summary 131

6 A Framework for Control in a Cylindrical and a Spherical Coordinate System 132
6.1 Introduction 132
6.2 Cylindrical and Spherical Coordinates 133
6.2.1 Cylindrical Coordinates 133
6.2.2 Spherical Coordinates 135
6.2.3 Operational Space Control Approach 135
6.3 Controller Structure 135
6.3.1 Task Controller 137
6.3.2 Integral Sliding Mode Controller 138
6.3.3 Posture Control For Grasping 139
6.3.3.1 Posture Control for Index and Thumb Finger 139
6.4 Compliance Control And Model Reference Behavior 141
6.4.1 Compliance 141
6.5 Summary 142

7 Practical Results in Cylindrical and Spherical Coordinates for Fixed Compliance and Adaptive Compliance 143
7.1 Introduction 143
7.2 Results 143
7.2.1 Test Objects 144
7.2.2 Posture Controller Parameters 146

7.2.3 Case 1: Tracking Results 146
7.2.3.1 Tracking Results for Ring Finger 146
7.2.3.2 Tracking Results for Index and Thumb Finger 146
7.2.4 Case 2: Results for Grasping in Cylindrical Coordinate for Fixed Compliance 149
7.2.5 Reference Model Parameters 149
7.2.6 Performance 149
7.2.7 Case 3: Results for An Automated Tuning Procedure 152
7.2.8 Reference Model Parameters 154
7.2.8.1 Results for Specific Object 154
7.2.8.2 Compliance level results for different objects 157
7.2.9 Automated Tuning Process-Discussion 159
7.3 Summary 159

8 Conclusions and Future Work **160**
8.1 Contributions 160
8.2 Discussion and Future Work 161

Appendix **164**
A MapleSim Results 164
B SPTS Specification 168
C MATLAB and Simulink: Excerpt of Simulink Layout for Robust Active Compliance Control 169
D Automatic Computation of G_f 171

References **173**

List of Figures

1.1 An ‘interacting’ Bristol Robot Hand 4

2.1 Rigid-body robot model with compliant sensor and rigid workpiece 13
2.2 A compliant human hand 14
2.3 A compliant robot hand 15
2.4 Examples of power grasping 22
2.5 Examples of precision grasping 22
2.6 Grasping constraint (http://www.cs.cmu.edu/ yingli/) 24
2.7 Underactuated robot hands (Elumotion [2010] and ShadowRobot [2003]) . 27
2.8 Derivation of forward kinematics for two links robot manipulator by using DH technique 29
2.9 Multiple solutions connected in configuration space for inverse kinematics . 31
2.10 A two degree of freedom robot arm 34
2.11 A contact object with a grasping hand 37
2.12 Tactile sensors are mounted on the robot fingers (Park *et al.* [2007] and Elumotion [2010]) 39
2.13 Definition of task X and joint q coordinates for 2 links robot manipulator [Spiers *et al.*, 2009] 44
2.14 Posture of 2 links robot manipulator that reach the same target height X_{y0} with different amounts of effort. The effort for (b) is significantly high than that in (a) [Spiers *et al.*, 2009] 46
2.15 A sliding manifold 48
2.16 Illustration of chattering phenomena 52

3.1 Underactuated BERUL fingers 62

3.2 A four-link constraint thumb . . . 64
3.3 RoboRealm Environment . . . 65
3.4 Measuring the relationships between joint 1(θ_1) and joint 2(θ_2), joint 2(θ_2) and joint 3(θ_3) . . . 68
3.5 Fingers Kinematics starts from resting state to fully flexed position . . . 69
3.6 Matlab computes linear relationships . . . 70
3.7 Forward kinematics for the BERUL hand . . . 74
3.7 Forward kinematics for the BERUL hand . . . 75
3.7 Forward kinematics for the BERUL hand . . . 76
3.8 Workspace for the BERUL fingers . . . 76
3.9 An illustration of a three link finger where the relationship of the joints can be computed . . . 78
3.10 An illustration of a pulley-belt system where the force and torque relationship can be computed . . . 79
3.11 The BERUL finger model using MapleSim . . . 82
3.12 The BERUL fingers model using SimMechanics . . . 83
3.13 Experimental setup for the BERUL fingers . . . 84
3.14 A complete experimental setup for the BERUL fingers . . . 85
3.15 DS1006 processor board (http://www.dspaceinc.com/) . . . 86
3.16 DS2002/DS2003 analog to digital conversion board . . . 87
3.17 The single point tactile sensor . . . 89
3.18 EPOS 24/1 and EPOS 24/5 units (http://www.dspaceinc.com/) . . . 90
3.19 EPOS message frame . . . 91

4.1 Block diagram of the adaptive control scheme . . . 96
4.2 Block diagram of the PID/SMC/ISMC control scheme . . . 97
4.3 Performance of PID control for thumb finger . . . 102
4.4 Stable performance of adaptive control for thumb finger for $\Gamma = 0.005$ (Table 4.2) . . . 103
4.5 Performance of SMC control for thumb finger . . . 105
4.6 Performance of ISMC control for thumb finger . . . 106
4.7 Performance of ISMC control when $\delta = 0.001$ . . . 107
4.8 Performance of ISMC control when $\delta = 1$ . . . 108

5.1 Block Diagram of the ISMC to achieve active compliance control for the BERUL fingers . . . 114
5.2 Compliant control for thumb finger of a -0.3 rad demand (flexional motion) 118
5.3 Compliant control for ring finger of a -0.3 rad demand (flexional motion) . 119
5.4 Stiffness level for thumb finger when $K_s = 4$, $K_{is} = 1$. . . . 121
5.5 Stiffness level for thumb finger when $K_s = 4$, $K_{is} = 6$. . . . 121
5.6 Stiffness level for thumb finger when $K_s = 4, K_{is} = 15$. . . . 122
5.7 Stiffness level for thumb finger when $K_s = 6, K_{is} = 1$. . . . 122
5.8 Stiffness level for thumb finger when $K_s = 12, K_{is} = 1$. . . . 123
5.9 Stiffness level for thumb finger . . . 126
5.10 Stiffness level for thumb finger . . . 127
5.11 Stiffness level for thumb finger . . . 128
5.12 Tested objects for practical compliance . . . 129
5.13 Results for tested objects of practical compliance . . . 130

6.1 Cylindrical coordinate system used for index, middle, ring and small finger 134
6.2 Spherical coordinate system used for thumb finger . . . 134
6.3 Block Diagram of the ISMC to achieve active compliance control for the BERUL fingers . . . 136

7.1 Tested objects for practical compliance . . . 145
7.2 a) R_d-tracking for thumb finger in Spherical coordinates; (b) and (c) R_d-tracking for index and ring finger in cylindrical coordinates . . . 147
7.3 Cylindrical orientation for index and ring finger while spherical motion for thumb finger . . . 148
7.4 Compliance for a spongy ball when $K_s = 4$, $K_{is} = 20$ and $G_f = 11.43$ . . 150
7.5 Compliance for a balloon when $K_s = 4$, $K_{is} = 15$ and $G_f = 8.57$ . . . 150
7.6 Compliance for a bottle when $K_s = 4$, $K_{is} = 30$ and $G_f = 17.1$ . . . 151
7.7 Automated tuning process of input gain (G_f) . . . 153
7.8 Compliance performance for level 0.08 psi (0.1 V) . . . 155
7.9 Compliance performance for level 0.32 psi (0.4 V) . . . 156
7.10 Compliance performance for level a $hard$ spongy ball . . . 157
7.11 Compliance performance for a $soft$ balloon . . . 158

List of Tables

2.1 Denavit-Hartenberg parameters 29

3.1 Link Parameters of the four-link thumb 72
3.2 Link Parameters of the four-link thumb after substitution (i.e substitute θ_1 for θ_2 and θ_3) 72

4.1 PID gain selection for thumb finger. 101
4.2 Adaptive gain selection for thumb finger. 103
4.3 SMC gain selection for thumb finger. 104
4.4 ISMC gain selection for thumb finger. 106
4.5 ISMC chattering effect for thumb finger 108
4.6 Summarized Normalized error and total control signal energy for thumb finger. (only stable period used for adaptive controller) 109
4.7 Normalized error for different 1^{st} order lowpass filters 110
4.8 Total control signal energy for different 1^{st} order lowpass filters 110
4.9 *Summed* trajectory normalized error and total relative control energy for other fingers (index, middle, ring, small). 111

5.1 Gain Selection for ISMC 118
5.2 Compliance Gain Selection (see (5.10) for computation of ω_n and ζ from K_s and K_{is}) 120
5.3 Information of thumb finger 124

7.1 Desired Force for level 0.08 psi (0.1 V) 155
7.2 Desired Force for level 0.32 psi (0.4 V) 156
7.3 Desired Force for level 0.2 psi (0.2 V) 157

7.4 Desired Force for level 0.2 psi (0.2 V) 158

List of Abbreviations

ACT	Anatomically-Correct Testbed
ADC	Analog to Digital Converter
$Anthrobot$	Anthropomorphic Robot Hand
$BERUL$	Bristol Elumotion Robot Hand
BRL	Bristol Robotics Laboratory
$Cybhand$	Cybernetics Robot Hand
$DART$	Dexterous Anthropomorphic Robotic Typing
DH	Denavit Hartenberg
DOF	Degree of Freedom
FBG	Fiber Bragg Grating
$ISMC$	Integral Sliding Mode Control
$LMEE$	Local Minimum of Elastic Potential Energy
PID	Proportional Integral Derivative
$PISMC$	Proportional-Integral Sliding Mode Control
RL	Reinforcement Learning
$SEAs$	Series Elastic Actuators
SMC	Sliding Mode Control
$SPTS$	Single Pressure Tactile Sensor
$STARMAC$	Stanford Testbed of an Autonomous Rotorcraft for Multi-Agent Control
$VSSs$	Variable-Structure Systems

List of Symbols

Z	impedance	19
k	stiffness	19
b	viscous damping coefficient	19
I_i	inertia	19
T_{gen}	generated torque	20
ω	actual speed	20
α	actual acceleration	20
τ	joint torque vector for modelling contact	33
M	mass matrix for modelling robot finger	33
V	resulting Coriolis matrix for modelling robot finger	33
G	gravitational force vector for modelling robot finger	33
F_r	friction force vector	33
q	joint position vector	33
q_f	coordinate vector describing the combined configuration of the system consisting of one or more parts and robot fingers	37
W	grasp matrix that maps the individual fingertip contact wrenches	37
f_{all}	vector obtained by stacking the wrench at an active contact	37
c_i	an active contact	37
M_f	mass matrix for modeling contact	37
C	resulting coriolis matrix for modelling contact	37
g	gravitational force vector for modelling contact	37
T_f	control forces for modelling contact	37
τ_f	joint torque vector for modelling contact	37
J	Jacobian	44

F	force	44
N^T	null space operation	45
I	identity matrix	45
U	cost function	45
K_a	actuator activation matrix	45
f_u	unknown but bounded some known functions of the states	47
s	sliding mode surface	48
c	constant	48
x	position error	47
M_i	constant	49
sgn	signum	49
$\dot{x}$	velocity error	48
q_e	tracking error	55
θ_1	angular data of joint 1	64
θ_2	angular data of joint 2	64
θ_3	angular data of joint 3	64
X_o	reference frame	72
Y_o	reference frame	72
Z_o	reference frame	72
VG_1	lumped expressions of coriolis/centrifugal force and gravity	78
VG_2	lumped expressions of coriolis/centrifugal force and gravity	78
VG_3	lumped expressions of coriolis/centrifugal force and gravity	78
T_1	actual torque joint 1	78
T_2	actual torque joint 2	78
T_3	actual torque joint 3	78
T_D	driving torque joint 1	78
T_{L21}	load torque joint 1	78
T_{L22}	driving torque joint 2	78
T_{L31}	load torque joint 2	78
T_{L32}	driving torque joint 3	78
r_1	radius of the first pulley	79
r_{21}	radius of the second pulley	79
k_{12}	constant to take into account offset	79

r_{22}	radius of the second pulley	79
r_3	radius of the third pulley	79
k_{22}	constant to take into account offset	79
f	lumped expression for the major nonlinearities	94
q_d	desired trajectory	94
$\dot{q}_d$	desired trajectory velocity	94
$\ddot{q}_d$	desired trajectory acceleration	94
r	filtered control error	95
$\dot{q}_r$	reference trajectory velocity	95
$\ddot{q}_r$	reference trajectory acceleration	95
λ	constant	95
k_1	constant	95
k_i	constant	95
$\hat{f}$	an estimate of the friction force	95
$\hat{M}$	an estimate of the mass	95
S	basis functions used for friction identification	95
P	a vector of parameters	95
ϵ	a small remaining error	95
$\tilde{f}$	actual of the friction force - estimate of the friction force	95
$\tilde{M}$	actual of the mass - estimate of the mass	95
u_r	compensate for any remaining modeling uncertainty ϵ	95
k_2	constant	95
$\dot{\hat{\theta}}$	adapting law	96
Γ	adapting law	96
ψ	adapting law	96
σ	a forgetting factor	96
τ_0	computed torque component	97
τ_1	discontinuous torque control	97
M_0	nominal value	97
f_0	a discontinuous torque control	97
K_P	positive scalars determining the sliding mode reaching performance	97
K_D	positive scalars determining the sliding mode reaching performance	97
Γ_0	gain to drive $s = 0$	97

K_s	gain for sliding surface/damping constant	97
K_{is}	integral gain for sliding mode control/spring constant	98
y_{di}	demand signals	99
y_i	output signals	99
N_s	number of samples	99
u_i	control signal	99
δ	gain to suppress chattering	115
H	external force measurement signal	115
G_f	input distribution gain	115
q_r	virtual demand	116
m_v	virtual mass of the spring	116
K_{ss}	virtual damping constant	116
K_{ii}	virtual spring constant	116
ω_n	natural frequency	116
ζ	damping ratio coefficient	116
R_d	desired radial	137
$\dot{R}_d$	desired radial velocity	137
$\ddot{R}_d$	desired radial acceleration	137
R_e	radial error	137
F_0	PD controller	138
F_1	integral sliding mode controller	138
B	projection matrix	139
$\hat{s}$	sliding mode variable for the posture control	139
δ_{SL}	gain to suppress chattering for the posture control	139
K_{dp}	constant	139
K_{SL}	constant	139
K_v	constant	139
w_1	constant	140
w_2	constant	140
ϕ_1	constant	140
ϕ_2	constant	140
R_r	virtual demand	142
H_{L1}	sensor level 1	152

H_{L2} sensor level 2 152

Chapter 1

Introduction

1.1 Background

1.1.1 General

One has to understand the history of humanoid robots to convey and develop ideas for the development of humanoid robots. The history of robots began with the word “Robot” [Karel, 2001] which stands for a laborer that originated from a Czechoslovak word “robota” (i.e. work), and represents the automaton which serves human beings as if it was a real creature, despite it is not alive. At the moment of their first emergence, they were given anthropomorphic shapes even before named “robot”. Their imaginary ancestors are Talose in Greek myths, robots in “R.U.R.” [Karel, 2001], Hadaly in “L ‘Eve future” [Harbou, 2003], Maria in “Metropolis” [Adam, 1993] and so forth. Robots appeared before approved as a field of science, e.g. Android designed by Vince [1945], Steam Man by Dederick [1868] or the first oriental android Gakutensoku by Nishimura [1929]. They are thought to be primitive humanoid robots and they were the very result of the curiosity towards ourselves. On the other hand, the history of robotics [Asimov, 1991] began with the control of manipulators [Goertz, 1952, 1954] at Argonne National Laboratory, which was a trial to realize a human-like device, particularly focusing on the arm function. Since then, robotics has been widely concerned with the functional mimicking of biological systems, not only the whole body type humanoid robots. In the early stage, robotics was mainly targeting the development of industrial robots which worked in limited environments such as plants.

During the seventies, Katoh [1973] developed WABOT-1, which was equipped with a visual recognition system, verbal communication system and a quasistatic walking controller. Then, Katoh *et al.* [1985] and Sugano *et al.* [1985] also developed WABOT-2. Though it did not have walking ability, it had visual and auditory sensations and succeeded to play the electronic organ. The history of humanoid robot research after Katoh [1973] is also the history of an evolution of their body, which are classified into i) the upperbody type, ii) the crawler type and iii) the whole body type. The upperbody type Humanoid Robots are the extension of industrial manipulators in the sense that they are fixed to the base. The study theme for them mainly lies on the fusion of intelligence and motor control. Fanuc Ltd. [Nakajima, 1985] developed a large size humanoid Fanuc man. At that time, humanoid robots have wheels or caterpillars on their lower bodies, so that they can locomote in the world. Tachi *et al.* [1989] developed Hadaly-2 with mechanically variable compliance on its arms, and studied the man-machine interaction and cooperation. Finally, the whole body type humanoid robots would have legs, and thanks to them, they can move on much rougher terrain than crawler type robots. Hirai [1997] and Hirai *et al.* [1998] developed P2, which was epoch-making not only in humanoid robotics but in the entire field of robotics. P2 is the world's first cable-less humanoid robot, which can walk and can go up/down stairs.

At present, some of the latest research on humanoid robots has focussed on different areas of the robot's body. For example, dexterous two-handed manipulators [Ott *et al.*, 2006] were investigated for the upper body of a robot. This robot is compliant through passivity based control approaches. However, the compliance control approach does not include the context of the surrounding world. The robot torso is safe but does not allow (social) interaction. Then, there is the study of a compliant humanoid robot, where the focus is on the lower part of the robot's body [Hyon *et al.*, 2007]. Hence, this project has successfully concentrated on balancing in the presence of unknown external forces. This project shows that the robot is successfully compliant but the controller is again not sufficient to allow context dependent compliance control. This shows that there is a significant need for an improved compliance control approach in humanoid robots and for a thorough investigation of a robot's body actions such that the robot can safely work with humans in the same environment.

1.1.2 Project Context

The focus of this project is on compliance control in robots, in particular for the humanoid robot hand which is capable of working in the same environment as humans and able to interact with humans and to grasp any objects safely (see Figure 1.1). This is motivated by the fact that the cost of human workforce is increasing and demographic studies have shown the general aging of population, which decreases the amount of accessible workforce. Hence, applications of humanoid robots can be seen in the area of maintenance tasks for industrial plants, security services of home and office, human care, teleoperations of construction machines, and cooperative work in the open air. In particular, the fields of service robotics, medical applications, and operation in hazardous environments are of primary importance. Moreover, in education, robots have always fascinated the young and old, and provide new and valuable tools for teachers in both classroom-based learning and excursion. A robot can also be a personal companion in which the robot is capable to accompany the user ranging from babysitting for children to personal assistant as well as loneliness companions. Moreover, in medical science the robots can provide vital help for patients which are in need of rehabilitation or simply comfort. This requires a robot to be equipped with sensors for monitoring vital signs and emotional states. The discussion above shows that the capability of the robot in order to replace human work force has become important and popular nowadays. Many research teams are working on the problem how a robot can move, act, talk, see and touch as good as a human [Hirai *et al.*, 1998], [Sakagami *et al.*, 2002], [Morita *et al.*, 1999], [Kaneko *et al.*, 2002], [Kim *et al.*, 2005]. A so called "humanoid robot" still requires vast improvements in many areas such as mobility, flexibility as well as security. However, research on the motion control and compliant control of humanoid is still in the midway due to the following factors:

1. A large number of degrees-of-freedom systems, consisting of more than 30 joints. (The Bristol humanoid robot has more than 40 joints, i.e. 7 joints for each arm, 2 torso joints, 1 neck joint and 12 joints for each hand.) Such a multibody system is highly nonlinear, so that it requires advanced nonlinear control approaches taking also account of the kinematics, i.e. complex relationships between the local coordinate system of each robot joint, and the nonlinear dynamics which naturally arise from such a complex robot.

2. The Bristol Robot is a highly redundant system (e.g. each arm has 7 joints to determine six degrees of movement of the endpoint of the arm actuator). This not only requires a good comprehension of position control or conversion from internal joint forces to the external reaction forces, through the interaction with the environment at

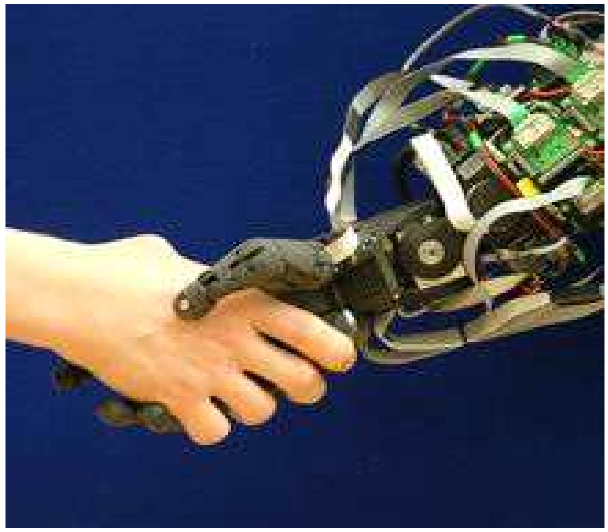


Figure 1.1: An ‘interacting’ Bristol Robot Hand

each contact point, but also a good understanding of the physiological (im)possibilities of a human(oid) robot: Although the arm is multiply redundant not every possible joint combination achieving a 6 degree target may be feasible as it may not be acceptable for a ‘human’ arm posture or it may even be dangerous.

3. A large number of underactuated systems have been built for robot hands. The fact that it is much easier to control a finger with one actuator rather than a fully actuated one is not always true. The transformation from one angle to another if the finger consists of 3 links with one actuator may vary at a desired end position. This will cause the difficulty to grasp an object accurately. Although an underactuated system may reduce the cost, a fully actuated finger can produce a more precise grasping manoeuver.

4. Structure-varying system: The total degrees of freedom vary as the contact state changes, i.e. it is collocated with the environment. Thus, resolving safety issues through compliance control in humanoid robots is a very challenging project as more than compliance for safety is required: The controller is to be used for a robot which has to ‘socially’ interact with humans rather than avoiding them. However, the humanoid robot is able to harm human beings since there are so many uncertainties occur during its implementation in the ever changing (social) context of the real world.

Hence, providing robust and active compliance control for the robot hand can be one of the solutions to resolve safety issues. This is however challenging since the problem as mentioned in items three and four of the preceding discussion may significantly affect the grasping performance. To demonstrate this, the Bristol Elumotion Humanoid Robot Hand (BERUL), which has been built to emulate characteristics close to a human hand, can be a very good platform to investigate a compliant control strategy. The BERUL hand should be able to grasp any object without damage. Moreover, the compliant controller via the BERUL hand has to satisfy not only (social) compliant interaction, but the controller has to exploit the highly redundant characteristics of the humanoid robot to achieve movement in the most human-like manner, i.e. the controller has to cater for social context dependent compliance, human posture and movement at the same time.

1.2 Problem Statement and Objectives

Achieving active compliance control in particular for the BERUL hand requires a robust control strategy. This is important due to the fact that the BERUL hand consists of significant stiction and friction. This is enhanced as the hand is light in weight and fragile. The hand of 9 degrees of freedom is a prototype, i.e. not well documented and modelled: all fingers, i.e. index, middle, ring and small finger consist of three links and three joints except the thumb finger. The thumb has four joints and four links. For the majority of the fingers, these joints are connected through a single, flexible push rod which is then actuated by a leadscrew mechanism that converts a linear movement into a rotary movement for an electrical motor. Nine servo motors have been attached to various fingers of the BERUL fingers. In particular, one motor actuator is used for the small and ring finger and two actuators used for the middle, index and thumb finger.

Furthermore, the kinematics of all fingers of the BERUL hand are not provided by the producer of the BERUL hand, thus, this certainly affects the performance of the controller during grasping an object. It becomes even more difficult when the BERUL hand is continuously subjected to improvement, change and repair. Consequently, modeling the robot hand in detail is only feasible to a limited extent. Moreover, the BERUL hand is classified as an underactuated system. This enhances the difficulty of control design. Hence, choosing an appropriate robust controller in this case may not be a trivial task in particular when nonlinearities may contribute to poor tracking performance.

A study by Armstrong *et al.* [2009] has shown that a human hand can safely grasp any cylindrical and cube objects of the same size within approximately one second from opening to closing state. This is a very important target to be achieved by a robot hand as the controller should be able to perform as close as possible to human hand speed. Moreover, human hand are composed of 19 joints with 21 degrees of freedom connected to 34 muscles that provide great flexibility [Choi *et al.*, 2008]. This allows the human hand firmly grasp any objects with minimal posture while maintaining the speed and compliant. As a result, this can be very challenging task due to the robot hand must also able to grasp with certain posture and speed without crushing the objects. However, note that accuracy of human grasping is limited [Choi *et al.*, 2008] i.e. errors of 10% would be acceptable (although the controllers presented here are accurate less than 5% error). Hence, taking into consideration the above mentioned problems, the objectives of the research are as follows:

1. To select a robust control scheme which can overcome stiction and friction in the robot hand.
2. To achieve good motion control where the robot hand is able to realize grasping within one to two seconds.
3. To devise a compliant control approach for the BERUL hand (i.e. the robot must be able to physically interact with objects/humans without causing damage or injury).
4. To enable robust and fast manipulation when in contact with an unknown environment.
5. To achieve different compliancy levels for a particular object and different objects, i.e. the controller has to adapt to the different object characteristics (e.g. a hard and a soft surface of the grasped objects).
6. To imitate human hand posture for grasping an object such as cylindrical and spherical grasping.

1.3 Methodology

Thus, some techniques which may be useful for the BERUL hand to achieve robust active compliance control are as follows:

1. Comparison of the suggested integral sliding mode control strategy with a PID controller, an adaptive controller and a conventional sliding mode controller. This allows to verify the most suitable control method to be used for the BERUL hand in order to overcome stiction and friction.

2. Exploitation of a sophisticated image capturing tool such as Roborealm to capture the kinematics data; use of Maple-Sim to develop a robot hand model and SimMechanics to test grasping performance through off-line simulation. All these tools can provide faster, safer and reliable results in simulation before a real time implementation can be carried out with low risk.

3. Development of a robust and active compliance control via an Integral Sliding Mode Controller (ISMC). The ISMC can introduce a model reference model approach where a virtual mass-spring damper system can be exploited. Together with ISMC, an adaptive control approach may also be considered to realise robust and active compliance control.

4. Development, exploration and study of a suitable grasping technique via a cylindrical and a spherical coordinate system.

5. Application of an operational space control approach to allow posture optimization for grasping.

6. Provision of an automatic tuning procedure for the compliance reference model.

1.3.1 Compliant Control Strategy

A core point of this thesis is to develop a robust (almost model-free) active compliance control. Two approaches seem to be the worth developing in a humanoid robot hand control environment:

1. Adaptive control.

2. Integral sliding mode control.

It is known that adaptive control is capable to work in highly nonlinear and uncertain environments and the design method is not time consuming. Adaptive control allows adaptation to large parameter changes in the robot and also better adjustment to unmodelled dynamics of the environment. The fact is that humanoid robots are highly nonlinear systems; therefore, adaptive control can be very helpful. Thus, adaptive control is a strong candidate for control, i.e. it will deserve more detailed discussion.

As a second major control technique, integral sliding mode control (ISMC), allows us to introduce the model reference control of a mass-spring damper system to achieve compliance control. Apart from that, the ISMC is able to overcome nonlinearities such as friction and stiction, emanated from a plant. It is expected that, the ISMC approach should allow for 'social' context compliance control. In order to measure the contact surface, a sensor must be integrated with the suggested control schemes. For this, we employ a single pressure tactile sensor (SPTS) which will be attached on the finger tip so that different contact surface can be measured. In principal, the SPTS uses capacitive-based conformable pressure sensor to accurately and reliably quantify applied forces. Moreover, for practical grasping (to a human-like extent), a newly introduced posture controller via an operational space control will be embedded into the compliance controller.

Note that other types of robust controllers such as H_∞, μ optimal control or gain scheduling are in this respect not investigated. Due to the simplicity and the practicality of the control design to achieve an active compliant control for the BERUL fingers, an adaptive control and an ISMC are more suitable control approaches (more detailed on common compliance control schemes is given in Chapter 2). The approaches of H_∞ or μ control lend themselves to a linear context while the problem of the hand is highly nonlinear. Moreover, much of the approaches used here in this thesis are model reference based, for which ISMC and adaptive control are highly suited.

1.4 Outline of the Thesis

Considering the statements about the problems and objectives of this research work the structure of the thesis is as follows:

Chapter 1: Introduction of the Thesis.

The chapter introduces the specific project to be carried out for the compliance control. The existing problem, objectives and methodology are highlighted and emphasized here.

Chapter 2: Literature Review.

The chapter provides the necessary background on compliance control. Besides gathering information in particular for active compliance control, other related work such as on kinematics, modelling and sensor technology are also outlined here. This will help us to monitor the past, recent and future research work, that need to be catered for or resolved.

Chapter 3: Kinematics, Dynamics and Experimental Set-Up.

The chapter shows the derivation of the forward kinematics of the robot hand by using the DH technique and introducing the video capturing tool, Roborealm, to capture the kinematics data in order to find out the relationship between two joints. The dynamical model of the BERUL fingers is provided. With the help of MapleSim, the model of the BERUL fingers can be represented in the Simulink environment. Additionally, with the help of SimMechanics, the model can be validated in simulation before it can be used in real time implementation. Moreover, the overall experimental set-up is discussed. The BERUL fingers have been controlled with MATLAB/Simulink and dSPACE which permit a simple and an easy way to carry out the experiment.

Chapter 4: Underactuated Fingers Controlled by Robust and Adaptive Trajectory Following Methods.

The chapter is in particular investigates four different controllers namely a conventional PID controller, an adaptive, a conventional sliding mode and an integral sliding mode controller. In this chapter, it is shown that sliding mode control methods are indeed highly suited to counteract nonlinearities while providing superior performance.

Chapter 5: A Novel Approach of Robust Active Compliance for Robot Fingers.

The chapter introduces a novel method to achieve active compliance control in simulation and real time implementation: Integral sliding mode control uses a model reference approach. A mass-spring damper system using an external force measurement for compliance is introduced as reference model. It is a robust technique to realize active compliance control for the BERUL fingers which are hampered by stiction and friction phenomena.

Chapter 6: A Framework for Control in a Cylindrical and a Spherical Coordinate System.
The chapter provides a principal concept for grasping an object via cylindrical and spherical coordinate systems. This improves a grasping technique by controlling the hand in particular the thumb finger via spherical coordinates and the other remaining fingers via cylindrical coordinates. It has been proven by previous work that commonly grasped objects are cylindrical, which makes the active control in cylindrical coordinates highly suitable for the index, middle, ring and small finger. On the other hand for the thumb finger, it has been found that the multi-redundant character of the thumb requires a more versatile task coordinate system. The thumb has to be able to move around any grasped object, in contrast to the other fingers. Thus, spherical coordinates are more suitable for the thumb. The chapter also considers an operational space control approach to resolve the problem that some of the fingers are actuated by more than one actuator, introducing redundancy. The redundant degrees of freedom are adjusted via a posture controller, a common part of any operational space controller.

Chapter 7: Practical Results in Cylindrical and Spherical Coordinates for Fixed Compliance and Adaptive Compliance.
The chapter demonstrates practical results for practical grasping via cylindrical and spherical coordinate systems. The chapter is also important to observe the effectiveness of the operational space control for practical grasping. The control design and the results for the choice of compliancy levels are provided for specific objects. For this, an automatic compliancy level for the object to be grasped is proposed. This proves that the proposed control algorithm (i.e. the ISMC) can be useful for achieving different levels of active compliance control for hard and soft surfaces.

Chapter 8: Conclusion and Future Work.
The chapter summarizes the main contribution of the thesis and future work.

Chapter 2

Literature Review

Over the years, humanoid robots have become of major interest of study among researchers in the robotic field. Researchers have in particular extensively explored and analyzed human structures, behaviors and biomechanics so that a human like robot can be realized. Among them, the Honda humanoid robot has been developed [Hirai *et al.*, 1998] which is a humanoid robot with two legs and two arms, able to walk not only forward and backward but also diagonally either to the right or left and turning in any direction as well. Moreover, the (intelligent) ASIMO [Neo *et al.*, 2008] which is capable of speaking, seeing and listening has been presented successfully. These are two examples that have motivated researchers to broaden robotic research in various fields such as communication systems, sensor technology, image processing and particularly research in compliance control as in Bristol for the robot hand of the Bristol Elumotion Robot (BERUL).

The hand is one of the most important sensory organs and actuators of the human body. It has the capability to distinguish a touched object in various forms such as object thickness, object softness and object weight. Eventually, the hand will respond accordingly when grasping such objects without damaging them. Likewise, a robot hand should be able to perform the same tasks before entering the human environment. Significant effort has been made to emulate as much as possible the functions and the size of a human hand: This can be found in (Jacobsen *et al.* [1984], ShadowRobot [2003], Grebenstein *et al.* [2011] and Borst *et al.* [2003]). A more advanced design of a robot hand has been introduced by Vandeweghe *et al.* [2004] where a special hand, an *Anatomically-Correct Testbed (ACT) hand* has been built mainly for the following purposes:

- As a telemanipulator that mimics both the active and passive dynamics of a human hand for precision teleoperation and prosthetics.
- As an experimental testbed to investigate the complex neural control of human hand movements,
- As a working physical model of the human hand for neuro- and plastic-surgeons to test new surgical reconstruction techniques for impaired hands.

According to Vandeweghe *et al.* [2004], none of the other mentioned robot hands are suitable for the above purposes since they are not anatomically-correct as compared to the ACT hand. Other designs which can be considered similar to the ACT hand can be seen in a paper on *Dexterous Anthropomorphic Robotic Typing (DART)* [Thayer & Priya, 2011]. The main design objective is to demonstrate that the hand could type on a computer keyboard. They claimed that a single DART hand could type at a rate of 20 words per minute, compared to the average human typing speed of 33 words per minute with two hands. Thayer & Priya [2011] further claimed that there is no other robotic hand that can accurately type at human speed.

Perfect design including a sophisticated prototype architecture and a powerful control scheme of the robot hand is indeed vital when using the hand in the human/object world. Essentially, the safety in particular for humans, the grasped objects and also for the robot, must be guaranteed before both worlds interact. One of the vital requirements is the provision of compliant robot hand control. A compliant robot hand is needed for grasping for human/objects but also for the safety of the robot hand itself. There are different aspects which need to be focused on, in order to achieve a compliant robot hand. Hence, this chapter aims to provide a literature review for compliance in robot hands. Other relevant topics which are required for the compliant control of a robot hand are also included and split into a few sections.

2.1 Compliance Control

Initially, it has been observed that there is a need of having compliance control in industrial robots in order to provide a flexible end effector that can be used for assembly tasks. Work such as welding, painting or deburring requires an accurate positioning control together with compliance to prevent damage of the parts caused by the end effector. An increase in cost is implied if highly accurate positioning control without compliance is used instead. This is usually avoided by companies. Therefore, compliance control for robots has been of interest for many years in industry [Wang *et al.*, 1998]. Another area where compliance control is highly suited, is for medical systems and haptics. The need for force and compliance control is a core requirement when using tools which are remotely operated and possibly enhanced through haptics [Katsura & Ohnishi, 2004]. In the case of this thesis, much of the focus is given to compliant grasping to allow the compliant handling of objects in human-robot interaction.

In the context of robot control, compliant control can be defined as the allowance of deviations from its own equilibrium position, depending on the applied external force. The equilibrium position of a compliant actuator is defined as the position of the actuator where the actuator generates zero force or zero torque [Ham *et al.*, 2009]. Hence, by this definition, compliance will allow us to minimize the impact during collision of an end-effector with the contact environment. In the case of robot fingers, compliance is the ability of robot fingers to grasp any object without damage. Moreover, in particular in our case, the adjustable or the controllable stiffness of the actuator is always acting like a mass, spring and damper system. This compliance model is depicted in Figure 2.1. The mass m_r, represents the effective moving mass of a robotic link. The viscous damper b_r is chosen to give the appropriate rigid-body mode to the unattached robot. While structural damping is very low, b_r includes the linearized effects of all of the other damping in the robot. The sensor has stiffness k_s and damping b_s. The workpiece is shown as a *ground state*. The robot actuator is represented by the input force F, and the state variable x_r measures the position of the robot mass.

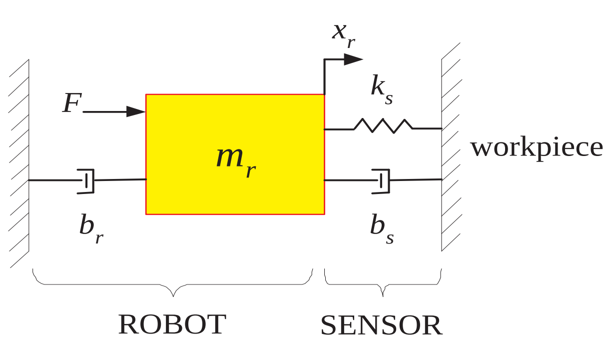


Figure 2.1: Rigid-body robot model with compliant sensor and rigid workpiece

The robot link dynamics of this simple system are described by the following transfer function:

$$\frac{X_r(s)}{F(s)} = \frac{1}{[m_r s^2 + (b_r + b_s)s + k_s]} \tag{2.1}$$

In this case, the model (2.1) can be used to adjust the compliance of the system by changing system stiffness and also damping. Passive methods do not use sensor data and generically rely on mechanical design. Active methods use the actuator F to modify the system model, either relying solely on PD-type control methods or also incorporating sensor data, e.g. a force sensor, to shape the system response. Much of this is discussed in this chapter.

Understanding human fingers can be the best example to design compliant control for robot fingers. Figure 2.2 shows that a human hand is able to adjust a grasping force without crushing the ball. On the other hand, Figure 2.3 illustrates a human-like robot. It employs an active controller for a model reference characteristic, replicating mechanical compliance, for a controller design. This will allow stiffness of the actuators to be adjusted.

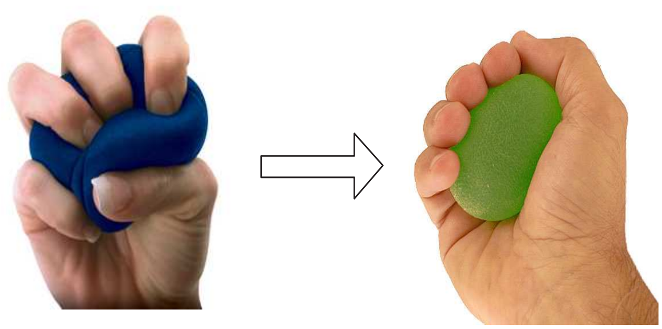
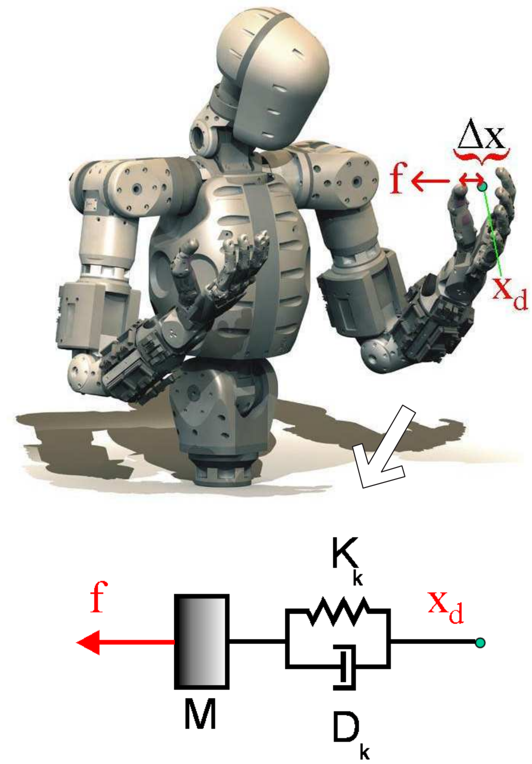


Figure 2.2: A compliant human hand



$$f = M\Delta\ddot{x} + D_k\Delta\dot{x} + K_k\Delta x$$

Figure 2.3: A compliant robot hand

2.1.1 Passive Compliance Control

Designing compliance for robots, in particular for multifingered robot hands, can be divided into three main categories. First, the design is solely based on passive compliance for which the use of linear springs is always preferable [Cutkosky, 1985], [Johnson, 1985], [Shimoga & Goldenberg, 1996]. Passive compliance is also regarded as a device or additional tool (usually spring and damper) that provides flexibility for the rigid robot. It is usually attached to the robot end-effector, such as at the hand, wrist, or fingers. As mentioned earlier, the primary demand for an industrial assembly can benefit from this passive compliance flexibility. Specifically, the adoption of passive compliance during assembly operation in robot manufacturing systems can guarantee that [Xu & Paul, 1990]:

1. the positioning tolerances in robot operation and the geometric uncertainties in the parts are relaxed,
2. the high forces or moments normally produced in jamming or wedging are reduced,
3. the assembled surfaces are protected from damage, such as a scraping or galling,
4. automatic assembly is facilitated to other operations,
5. expensive electronics normally required in precision operations can be eliminated.

Another advantage by employing passive compliance can be seen when gripping or grasping an object during an assembly process: The switching between two states is avoided in contrast to some active control methods, for example hybrid control. The first of a hybrid controller state is controlling the positioning error which is also known as controlling an unconstrained mode while the second state is providing force control for which a constrained mode must be considered. Between these two states, there is a transition mode (i.e. switching mode) from positioning control to force control where the force and velocity may discontinuously be achieved and become uncertain. This discontinuity and uncertainty can cause damage to the grasped object and can be avoided by employing passive compliance near the contact point of the end effector. In this case, the kinetic energy that is produced during transition can be absorbed and the possible high forces or moments can be prevented. Hence, the discontinuity is accommodated for and performance of the entire system becomes smoothed [Paul, 1987], [Xu & Paul, 1988], [Paul *et al.*, 1988].

Moreover, a high gain of the force control can be selected when the robot is equipped with a compliance device. Roberts *et al.* [1985] have shown that the allowable force control gain is proportional to the effective stiffness of the overall system. Therefore, for the system including passive compliance, the allowable force control gain is higher than that without passive compliance, which is desirable for improving sensitivity and performance of force control. Wang *et al.* [1998] have addressed in their survey some other advantages of passive compliance as follows:

- Can achieve very high stiffness,
- Guarantees overall stability due to its passive nature,
- Relatively cheap as compared to active compliance (expensive for some applications),

- Fast response rate.

Nevertheless, passive compliance has its own disadvantages such as positioning control is no longer accurate due to the reduction of the stiffness of the end effector. More problems have also been outlined by Wang *et al.* [1998] as follows:

- Mainly hardware achievable,
- Compliance center is usually fixed which causes lack of flexibility,
- Static/quasi-static compliance, i.e. fixed compliance dynamics
- Hard but possible to consider the compliance dynamics by special design with stiffness, damping and inertia factors taken into account.

2.1.2 Recent Developments in the Area of Passive Compliance

The work in [Akella & Cutkosky, 1989], [Sinha & Abel, 1992], [Shimoga & Goldenberg, 1996],[Xydas & Kao, 1999], [Arimoto *et al.*, 2000], [Biagiotti *et al.*, 2005], [Yoshida *et al.*, 2008], [Yamazaki *et al.*, 2009] has focused on deformable soft fingers as an alternative way to achieve compliant robot fingers. They were exploiting an advantage of visco-elastic material which has been used in soft pads. These soft pads will allow to compensate the dynamics effects such as shocks and vibration by dissipating the energy during manipulation. At an early stage, Akella & Cutkosky [1989] have attempted to model soft fingertips that were filled with powder or plastic fluid for controlling one degree of freedom grasping. A few researchers have used soft skin fingers made from elastic gel for grasping purpose, e.g. Yoshikawa *et al.* [2008] and Sugiyama *et al.* [2009]. Then, the latest studies by Yamazaki *et al.* [2009] have emphasized on two degrees of freedom grasping by describing the dynamic model of a pair of 2-DOF soft fingers and formulating a new controller as well as the equations of motion of soft fingered manipulation. In general, research groups for soft fingers limit their grasping technique to 1 DOF or 2 DOFs only. The advancement of the technique to more degrees of freedom requires modelling for deformation of soft finger which is very difficult to realize in practice. More interestingly, a new compliant grasping technique has been introduced by Brown *et al.* [2010]. His group has replaced a multifingered hand with a mass of granular material. This granular material which is filled in a single nonporous elastic bag is able to conform to the shape of the object during contact. The success of this grasping technique is based on the concepts of friction, suction, and interlocking mechanisms that are incorporated with granular material.

2.1.3 Active Compliance Control

On the other hand, active compliance may be an alternative where sensors and proper control action are employed [Liu *et al.*, 2004], [Kugi *et al.*, 2008], [Albu-Schaffer *et al.*, 2007], [Khan *et al.*, 2010], [Chen *et al.*, 2010]. Specifically, active compliance is achieved through joint-torques in the robot links, either by setting a linear relation between the force and displacement or force and velocity. Work such as impedance control [Hogan, 1984], [Hogan, 1987], damping control [Whitney, 1977], stiffness control [Salisbury, 1980] and resolved acceleration control [Luh *et al.*, 1980], [Shin & Lee, 1985] is relevant to active compliance control via different techniques. The pioneering work on impedance and compliance control has been carried out by Hogan [1985] and Kazerooni *et al.* [1986]. They have proven that active compliance control can be easily produced via a simple PD control. A similar PD control scheme has been tested by Tomei [1991], Liu *et al.* [2004], Kugi *et al.* [2008], Albu-Schaffer *et al.* [2007] and Chen *et al.* [2010] for their respective prototype robot hands. Although active compliance control can be achieved via a simple PD control approach. In many cases a robust controller method is preferable such as by Colbaugh *et al.* [1995] and Khan *et al.* [2010] of BRL. Both groups have used force sensors to produce a model reference compliance control strategy. For this, they have employed an adaptive compliance control scheme for a kinematically-redundant manipulator. An interesting application by utilizing active compliance control has been demonstrated by Mouri *et al.* [2007] for skin massage where a multifingered hand can perform pushing massage and rubbing massage. The authors have employed position-based impedance control and force-based impedance control to realize pushing and rubbing tasks.

Wang *et al.* [1998], on their study for compliance control robotic assembly systems, again have listed explicitly advantages and disadvantages of active compliance control. The advantages are as follows:

- Software achievable
- Easy to regulate and compute, which can benefit general use,

- Compliance center can be easily moved,
- Dynamic compliance,
- Easy to incorporate the system dynamics and force feedback information into the system so that the mechanical impedance of the robot end-effector can be controlled; possible to achieve negative compliance in the principal axis.

Disadvantages are outlined as below:

- Mainly software achievable (Note that software achievability can also be an advantage, However, the use of software may also introduce issues of safety and failure.),
- Suffers from the kinematic singularity,
- Since the Jacobian matrix of the robot kinematics is involved in the position and force transformation between the joint frames and end-effector frame, force and torque control are difficult in certain postures (e.g. kinematics singularities),
- Instability is often observed in active compliance control and careful attention is needed,
- For position control, there is an upper limit on the desired stiffness to avoid oscillation or instability,
- Relatively expensive (cheap for some applications),
- Limited response rate (normally suitable at low frequency),
- For any digital control system, the sampling rate determines the dynamic response of the active compliance and cannot be too fast, and the response rate also depends on the control law used.

A study to improve the limitation of the frequency range used for active compliance control has been investigated by Sensinger & Weir [2006] where the group has attempted to minimize one or more of the components of impedance (Z), namely stiffness (k), viscous (b), and inertial (I_i) components. The generated torque is a function of these three terms:

$$T_{gen} = k(\theta - \theta^*) + b\omega + I_i\alpha \tag{2.2}$$

where T_{gen} is the torque generated, θ is the actual position, θ^* is the desired position, ω is the actual speed and α is the actual acceleration. The technique, called Series Elastic Actuators (SEAs) is capable of achieving low impedance across all frequencies. By minimizing the impedance in particular for robot manipulators, this will allow low forces for a given perturbation at all frequencies i.e. have low impedance at high frequencies and not only in the actuators stable bandwidth.

2.1.4 Hybrid Active/Passive Compliance Control

It has been shown that both active and passive compliance techniques may have advantages and disadvantages. The last category, the so called *hybrid compliance*, which is a combination between active and passive compliance, may suit some applications [Jaura *et al.*, 1998], [Okada *et al.*, 2000], [Schiavi *et al.*, 2009]. This category seems to open more routes for compliance research by taking into consideration the advantages of passive compliance and active compliance. For example, Jaura *et al.* [1998] have examined the effect of the exerting force at the end effector when hybrid compliance control for an intelligent assembly in a robot work cell was employed. The results showed that the stiffness level is better when compared to the solely passive compliance used in the system. Okada *et al.* [2000], have optimized their work by exploiting active compliance at a low frequency range while passive compliance is used at a high frequency level for controlling a humanoid shoulder mechanism. More challenging work has been presented by Davies *et al.* [1997] for which hybrid compliance has been deployed to replace the bearing surfaces in the knee for a prosthetic implant. It is obvious that several techniques can be used to achieve grasping compliance control for a robot hand. The fact that, there is no unique solution to grasp various objects surfaces, has diversified the approaches for grasping control.

2.1.5 Compliance Level

In addition to compliance control, obtaining the correct compliance level is also vital. For example, robot fingers may require higher stiffness to hold a glass than a balloon. Hence, not only the compliance is important, but the level of stiffness is also crucial for different objects. Brown *et al.* [2010] have proven that their method was able to grasp various objects such as a LED, a light bulb, a glass, a pen and an egg. Yussof *et al.* [2008], have revealed their proposed algorithms are capable to detect the slippage of a grasped cup when filled with water. The sudden change of an object's weight has been sensed by an optical three-axis tactile sensor which has 41 array sensing elements that mimic the structure of human fingertips. Similar stiffness level control ideas for changing an object's weight can also be found in Tsujiuchi *et al.* [2003] for the Gifu hand.

2.2 Hand Grasping

Grasping can be regarded as one of the main functions for a humanoid robot. Shaking a hand, holding a glass, pouring water, passing an egg and writing by using a pen are examples for robot hand functionality that may have to be carried out. For a human, executing those tasks is very simple and straightforward. However, for the robot hand, it requires a study of many aspects such as positioning control, sensor or dynamic control in order to realize simple grasping. Again, a simple task such as holding a tennis ball can be very delicate and difficult for a robot hand to carry out. Kvrgic [1996] in his work has pointed out the complexity during grasping an object. In many cases, the grasping force and moment components are neglected due to the modeling difficulty. As a result, some of the available methods treat the finger and object contact as a point contact with Coulomb friction instead of surface contacts with Coulomb friction. This simplifies a grasping design for robot hands. In general, the robotic hands are still a long way from matching the grasping and manipulation capability of their human counterparts and there is no unique solution for a grasping hand and the contact to an object. Thus, this has created many options for the solution of hand-object grasping.

Grasping for the robot hand can be divided into two basic groups namely power grasping and precision grasping [Napier, 1956], [Al-Gallaf *et al.*, 1993], [Johan Tegin, 2005]. Power grasping can be seen when a larger object is held up by a simple manipulation task. For example, grasping and lifting a chair and holding a heavy tool are much easier than holding an egg or a pen. Power grasping is usually performed using the palm of the hand and almost every area of each finger during grasping or holding. Arimoto [2004], in his survey on intelligent control of multi-fingered hands said that power grasping can be realized without using any sensory feedback if the contact force exerted on an object can be adequately controlled. In other words, we can simply say that power grasping is closing the hand around the object without knowing the final contact points between the hand and the object. Figure 2.4 shows the examples of power grasping.

On the other hand, when it comes to precision grasping, more delicate objects such as an

Figure 2.4: Examples of power grasping
(http://cg.cis.upenn.edu/hms/research/RIVET/graspTypeRecog.pdf)

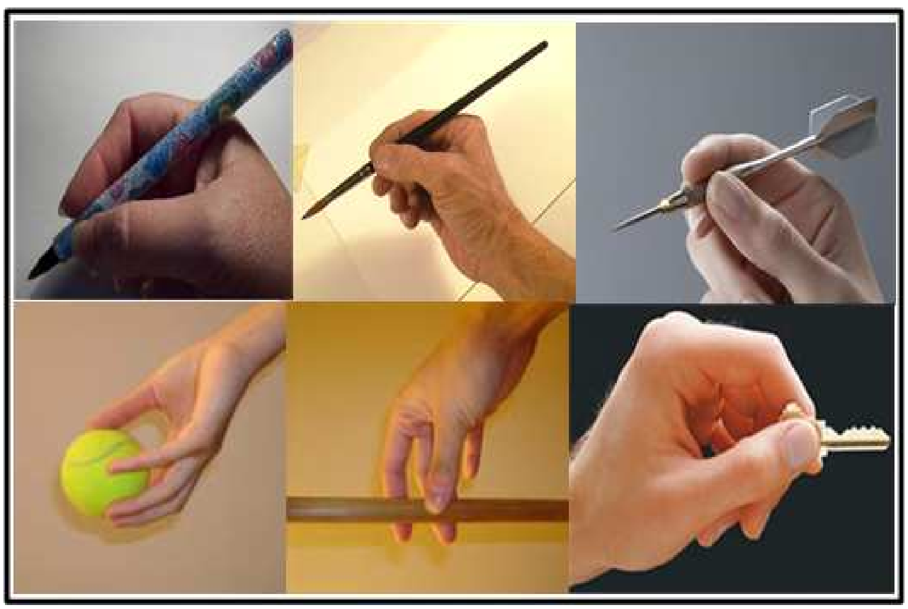
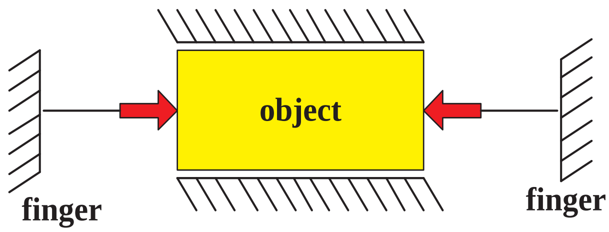


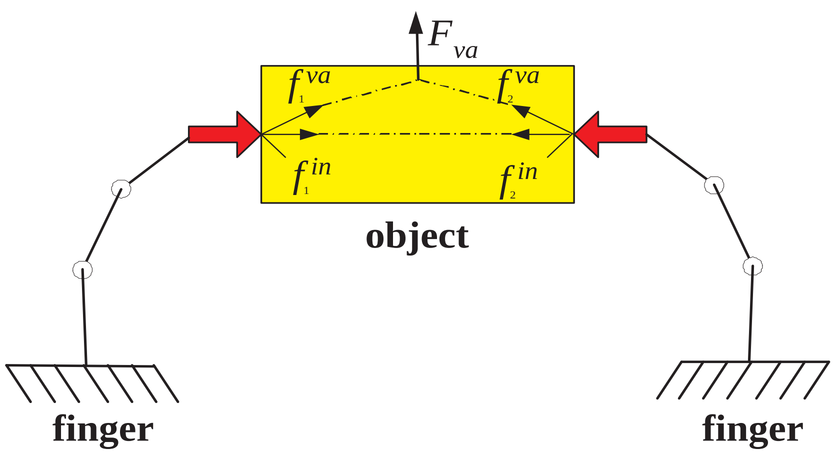
Figure 2.5: Examples of precision grasping
(http://cg.cis.upenn.edu/hms/research/RIVET/graspTypeRecog.pdf)

egg and a pen are considered (see Figure 2.5). It requires the hand to be more sensitive when it touches the surface of the object. In many cases, precision grasping uses fingertips which are equipped with more powerful sensors. In contrast to power grasping, the contact points are known during precision grasping.

In order to understand grasping techniques for a robot hand, a study based on a partial taxonomy of manufacturing grasps has been proposed by Cutkosky & Wright [1986]. The group has done an observation on single-handed operations by machinists which were working with metal parts and hand tools. They have found that power and precision grasping can be further detailed into smaller groups such as prehensile (clamping required) and non-prehensile (clamping not required). As such, the results showed that, in general, grasping can be easily achieved by a hand but hardly realized by a robot hand. Although, a lot of effort has been devoted to copy a human hand such as in Vandeweghe *et al.* [2004] and Thayer & Priya [2011], none of the robot hand designs so far can beat the human hand.



(a) Form-closure: Object is totally constrained



(b) Force-closure: Force and moment can be applied on the object

Figure 2.6: Grasping constraint (http://www.cs.cmu.edu/ yingli/)

References

ADAM, V.D.L. (1993). *L'Eve Future*. Berlin, BB, Germany.

AKELLA, P. & CUTKOSKY, M. (1989). Manipulating with soft fingers: modeling contacts and dynamics. In *IEEE International Conference on Robotics and Automation*, vol. 2, 764 –769.

AKIN, D., CARIGNAN, C. & FOSTER, A. (2002). Development of a four-fingered dexterous robot end effector for space operations. In *IEEE International Conference on Robotics and Automation*, vol. 3, 2302 –2308.

AL-GALLAF, E., ALLEN, A. & WARWICK, K. (1993). A survey of multi-fingered robot hands: Issues and grasping achievements. *Mechatronics*, **3**, 465 – 491.

ALBU-SCHAFFER, A., OTT, C. & HIRZINGER, G. (2007). A unified passivity-based control framework for position, torque and impedance control of flexible joint robots. *The International Journal of Robotics Research*, **26**, 23–39.

AMBROSINO, G., CELEKTANO, G. & GAROFALO, F. (1984). Variable structure model reference adaptive control systems. *International Journal of Control*, **39**, 1339–1349.

ARAI, H., TANIE, K. & SHIROMA, N. (1997). Feedback control of a 3-DOF planar underactuated manipulator. In *IEEE International Conference on Robotics and Automation*, vol. 1, 703–709.

ARIMOTO, S. (2004). Intelligent control of multi-fingered hands. *Annual Reviews in Control*, **28**, 75 – 85.

ARIMOTO, S., NGUYEN, P.T.A., HAN, H.Y. & DOULGERI, Z. (2000). Dynamics and control of a set of dual fingers with soft tips. *Robotica*, **18**, 71–80.

ARMSTRONG, T.J., BEST, C., BAE, S., CHOI, J., GRIESHABER, D.C., PARK, D., WOOLLEY, C. & ZHOU, W. (2009). Development of a Kinematic Hand Model for Study and Design of Hose Installation. In *Human-Computer Interaction*, 85–94.

ASADA, H. & SLOTINE, J.J.E. (1979). *Studies on prehension and handling by robot hands with elastic fingers*. Ph.D. dissertation, Kyoto University.

ASADA, H. & SLOTINE, J.J.E. (1986). *Robot Analysis and Control*. John Wiley and Sons, Inc.

ASIMOV, I. (1991). *i Robot*. Reprint edition.

BAE, J.H., ARIMOTO, S., SEKIMOTO, M. & OZAWA, R. (2004). Dexterity analysis of human and robotic grasping motions from the viewpoint of dynamics. In *IEEE International Conference on Robotics and Biomimetics*, 101–106.

BARTOLINI, G., FERRARA, A. & USANI, E. (1998). Chattering avoidance by second-order sliding mode control. *IEEE Transactions on Automatic Control*, **43**, 241 –246.

BASIN, M., FRIDMAN, L., RODRIGUEZ-GONZALEZ, J. & ACOSTA, P. (2003). Optimal and robust sliding mode control for linear systems with multiple time delays in control input. *Asian Journal of Control*, **5**, 557–567.

BASIN, M., RODRIGUEZ-GONZALEZ, J., FRIDMAN, L. & ACOSTA, P. (2005). Integral sliding mode design for robust filtering and control of linear stochastic time-delay systems. *International Journal of Robust and Nonlinear Control*, **15**, 407–421.

BEJARANO, F.J., FRIDMAN, L. & POZNYAK, A. (2007). Output integral sliding mode control based on algebraic hierarchical observer. *International Journal of Control*, **80**, 443–453.

BEKEY, G., LIU, H., TOMOVIC, R. & KARPLUS, W. (1993). Knowledge-based control of grasping in robot hands using heuristics from human motor skills. *IEEE Transactions on Robotics and Automation*, **9**, 709 –722.

BIAGIOTTI, L., MELCHIORRI, C., TIEZZI, P. & VASSURA, G. (2005). Modelling and identification of soft pads for robotic hands. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2786 – 2791.

BIRGLEN, L. & GOSSELIN, C. (2003). Kinetostatic analysis of underactuated fingers. *IEEE International Conference on Robotics and Automation*, **1**, 1139–1145.

BIRGLEN, L. & GOSSELIN, C. (2004). Kinetostatic analysis of underactuated fingers. In *IEEE Transactions on Robotics and Automation*, vol. 20, 211–221.

BIRGLEN, L., GOSSELIN, C. & LALIBERT, T. (2008). *Underactuated Robotic Hands*. Springer-Verlag, Berlin Heidelberg.

BONA, B. & INDRI, M. (2005). Friction compensation in robotics: an overview. In *IEEE Conference on Decision and Control: European Control Conference. CDC-ECC*, 4360 – 4367.

BONA, B., INDRI, M. & SMALDONE, N. (2006). Rapid prototyping of a model-based control with friction compensation for a direct-drive robot. *IEEE/ASME Transactions on Mechatronics,*, **11**, 576 –584.

BONDAREV, A., S.A. BONDAREV, N., KOSTYLEVA & UTKIN, V. (1985). Sliding modes in systems with asymptotic state observers. *Automation and Remote Control*, **46**, 49–64.

BORST, C., FISCHER, M., HAIDACHER, S., LIU, H. & HIRZINGER, G. (2003). DLR hand ii: experiments and experience with an anthropomorphic hand. In *IEEE International Conference on Robotics and Automation*, vol. 1, 702–707.

BOUGHDIRI, R., BEZINE, H., SIRDI, N., NAAMANE, A. & ALIMI, A. (2011). Dynamic modeling of a multi-fingered robot hand in free motion. In *International Multi-Conference on Systems, Signals and Devices (SSD)*, 1 –7.

BOWERS, D. & LUMIA, R. (2003). Manipulation of unmodeled objects using intelligent grasping schemes. *IEEE Transactions on Fuzzy Systems*, **11**, 320 – 330.

BROCK, D. (1988). Enhancing the dexterity of a robot hand using controlled slip. In *IEEE International Conference on Robotics and Automation*, vol. 1, 249 –251.

BROWN, E., RODENBERG, N., AMEND, J., MOZEIKA, A., STELTZ, E., ZAKIN, M.R., LIPSON, H. & JAEGER, H.M. (2010). Universal robotic gripper based on the jamming of granular material. *Proceedings of the National Academy of Sciences*.

BURTON, J.A. & ZINOBER, A.S.I. (1986). Continuous approximation of variable structure control. *International Journal of Systems Science*, **17**, 875–885.

CAI, C. & ROTH, B. (1986). On the planar motion of rigid body with point contact. In *Mechanism Machine Theory*, vol. 21, 453–466.

CANUDAS, C., ASTROM, K. & BRAUN, K. (1987). Adaptive friction compensation in DC-motor drives. In *IEEE Journal of Robotics and Automation*, vol. 3, 681–685.

CANUDAS DE WIT, C. & GE, S. (1997). Adaptive friction compensation for systems with generalized velocity/position friction dependency. In *IEEE Conference on Decision and Control*, vol. 3, 2465–2470 vol.3.

CARDIEL, L. & BEN GHALIA, M. (2004). A three element sliding mode control system for robot manipulators. *Region 5 Conference: Annual Technical and Leadership Workshop*, 21–30.

CASTANOS, F. & FRIDMAN, L. (2006). Analysis and design of integral sliding manifolds for systems with unmatched perturbations. *IEEE Transactions on Automatic Control,*, **51**, 853 – 858.

CHANG, J.L. (2009). Dynamic output integral sliding-mode control with disturbance attenuation. *IEEE Transactions on Automatic Control,*, **54**, 2653 –2658.

CHEN, Z., LII, N., WIMBOECK, T., FAN, S., JIN, M., BORST, C. & LIU, H. (2010). Experimental study on impedance control for the five-finger dexterous robot hand DLR-HIT II. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 5867 –5874.

CHENG, F.T., CHEN, T.H. & SUN, Y.Y. (1991). Inverse kinematic solutions for redundant manipulators using compact formulation. In *IEEE/RSJ International Workshop on Intelligent Robots and Systems (IROS)*, vol. 1, 153 –158.

CHOI, C., SHIN, M., KWON, S., PARK, W. & KIM, J. (2008). Understanding of hands and task characteristics for development of biomimetic robot hands. In *Humanoid Robots, 2008. Humanoids 2008. 8th IEEE-RAS International Conference on*, 413 –417.

CHRISTINE, L.M. & IBERALL, T. (1994). *The grasping hand*. Elsevier Science B.V.

CIOCARLIE, M., LACKNER, C. & ALLEN, P. (2007). Soft Finger Model with Adaptive Contact Geometry for Grasping and Manipulation Tasks. In *World Haptics*.

COLBAUGH, R., SERAJI, H. & GLASS, K. (1995). Adaptive compliant motion control for dexterous manipulators. *The International Journal of Robotics Research*, **14**, 270–280.

CONKUR, E.S. & BUCKINGHAM, R. (1997). Clarifying the definition of redundancy as used in robotics. *Robotica*, **15**, 583–586.

CORRALES, J., JARA, C. & TORRES, F. (2010). Modelling and simulation of a multi-fingered robotic hand for grasping tasks. In *International Conference on Control Automation Robotics Vision (ICARCV)*, 1577 –1582.

CRAIG, J. (1989). *Introduction to Robotics: Mechanics and Control 2nd Edition*. Addison-Wesley Publishing Company.

CROWDER, R.M. (1998). Course notes.

CURK, B. & JEZERNIK, K. (2001). Sliding mode control with perturbation estimation: application on DD robot mechanism. In *Robotica*, vol. 19, 641–648.

CUTKOSKY, M. (1989). On grasp choice, grasp models, and the design of hands for manufacturing tasks. *IEEE Transactions on Robotics and Automation*, **5**, 269 –279.

CUTKOSKY, M. & WRIGHT, P. (1986). Modeling manufacturing grips and correlations with the design of robotic hands. *IEEE Transactions on Robotics and Automation*, 1533–1539.

CUTKOSKY, M.R. (1985). *Robotic Grasping and Fine Manipulation*. Kluwer Academic Publishers, Norwell, MA, USA.

CUTKOSKY, M.R. & HOWE, R.D. (1990). *Human grasp choice and robotic grasp analysis*, 5–31. Springer-Verlag New York, Inc., New York, NY, USA.

DAVIES, B.L., HARRIS, S.J., LIN, W.J., HIBBERD, R.D., MIDDLETON, R. & COBB, J.C. (1997). Active compliance in robotic surgery–the use of force control as a dynamic constraint. *Proceedings of the Institution of Mechanical Engineers Part H Journal of engineering in medicine*, **211**, 285–292.

DE LUCA, A. & FERRAJOLI, L. (2009). A modified Newton-Euler method for dynamic computations in robot fault detection and control. In *IEEE International Conference on Robotics and Automation (ICRA)*, 3359 –3364.

DE MONTIGNY, M. & SICARD, P. (1999). Adaptive force/position control of a robot hand. In *IEEE Canadian Conference on Electrical and Computer Engineering*, vol. 3, 1392 –1397.

DE WIT, C.C., OLSSON, H., ASTROM, K. & LISCHINSKY, P. (1993). Dynamic friction models and control design. In *American Control Conference*, 1920–1926.

DEDERICK, Z.P. (1868). *Steam Man*. davidbuckley.net.

DEFOORT, M., FLOQUET, T., KOKOSY, A. & PERRUQUETTI, W. (2006). Integral sliding mode control for trajectory tracking of a unicycle type mobile robot. *Integrated Computer-Aided Engineering*, **13**, 277–288.

DESAPIO, V., WARREN, J., KHATIB, O. & DELP, S. (2005). Simulating the task-level control of human motion: a methodology and framework for implementation. *The Visual Computer*, 289–302.

DOULGERI, Z. & ARIMOTO, S. (1999). A force commanded impedance control for a robot finger with uncertain kinematics. *The International Journal of Robotics Research*, **18**, 1013–1029.

DSPACE (2010). dspace. `http://www.dspaceinc.com/`.

EDWARDS, C. & SPURGEON, S. (1994). Robust nonlinear control of heating plant. In *IEE Proceedings in Control Theory and Applications*, vol. 141, 227–234.

EKER, I. & AKINAL, S. (2008). Sliding mode control with integral augmented sliding surface: design and experimental application to an electromechanical system. *Electrical Engineering (Archiv fur Elektrotechnik)*, **90**, 189–197.

ELUMOTION (2010). Elumotion. `http://www.elumotion.com/`.

EMELYANOV, S.V. (1959). Control of first order delay systems by means of an astatic controller and nonlinear corrections. *Automatic Remote Control*, **8**, 983991.

FATIKOW, S. & SUNDERMANN, K. (1994). Neural-based learning in grasp force control of a robot hand. *Annual Review in Automatic Programming*, **19**, 111 – 116.

FEARING, R. (1986). Implementing a force strategy for object re-orientation. In *IEEE International Conference on Robotics and Automation*, vol. 3, 96 – 102.

FENG, C.C. (2011). Integral sliding-based robust control. *InTech*.

FILIPPOV, A. (1988). *Differential Equations with Discontinuous Righthand Sides,*. Springer.

FISHER, W. & MUJTABA, M. (1992). Sufficient stability condition for hybrid position/force control. In *IEEE International Conference on Robotics and Automation*, vol. 2, 1336 – 1341.

FUNDA, J. & PAUL, R. (1990). A computational analysis of screw transformations in robotics. *IEEE Transactions on Robotics and Automation*, **6**, 348 –356.

GE, S., LEE, T. & REN, S. (2001). Adaptive friction compensation of servo mechanisms. *International Journal of Systems Science*, **32**, 523–532.

GENG, T., LEE, M. & HLSE, M. (2011). Transferring human grasping synergies to a robot. *Mechatronics*, **21**, 272 – 284.

GENTNERS, S. (2010). Roborealm. `http://www.roborealm.com/`.

GLOVER, J., RUS, D. & ROY, N. (2009). Probabilistic models of object geometry with application to grasping. *International Journal of Robotics Research*, **28**, 999–1019.

GOERTZ, R.C. (1952). Fundamentals of general-purpose remote manipulators. *Nucleonics*, **10**, 36–42.

GOERTZ, R.C. (1954). Electronically controlled manipulator. *Nucleonics*, **12**, 46–47.

GREBENSTEIN, M., ALBU-SCHAFFER, A., BAHLS, T., CHALON, M., EIBERGER, O., FRIEDL, W., GRUBER, R., HADDADIN, S., HAGN, U., HASLINGER, R., HOPPNER, H., JORG, S., NICKL, M., NOTHHELFER, A., PETIT, F., REILL, J., SEITZ, N., WIMBOCK, T., WOLF, S., WUSTHOFF, T. & HIRZINGER, G. (2011). The DLR hand arm system. In *IEEE International Conference on Robotics and Automation (ICRA)*, 3175 –3182.

HAM, R., SUGAR, T., VANDERBORGHT, B., HOLLANDER, K. & LEFEBER, D. (2009). Compliant actuator designs. *Robotics Automation Magazine, IEEE*, **16**, 81 –94.

HARBOU, T.V. (2003). *Metropolis*. Berlin, BB, Germany.

HERRMANN, G., GE, S. & GUO, G. (2005). Practical implementation of a neural network controller in a hard disk drive. *IEEE Transactions on Control Systems Technology*, **13**, 146 – 154.

HERRMANN, G., SPURGEON, S. & EDWARDS, C. (2006). On robust, multi-input sliding-mode based control with a state-dependent boundary layer. *Journal of Optimization Theory and Applications*, **129**, 89–107.

HERRMANN, G., TURNER, M.C. & POSTLETHWAITE, I. (2008). A robust override scheme enforcing strict output constraints for a class of strictly proper systems. *Automatica*, 753–760.

HIRAI, K. (1997). Current and future perspective of honda humamoid robot. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, vol. 2, 500 –508.

HIRAI, K., HIROSE, M., HAIKAWA, Y. & TAKENAKA, T. (1998). The development of honda humanoid robot. In *IEEE International Conference on Robotics and Automation*, vol. 2, 1321–1326.

HOGAN, N. (1980). Mechanical impedance control in assistive devices and manipulators. *Proceedings of the Joint Automatic Controls Conference*, **1**.

HOGAN, N. (1984). Impedance control of industrial robots. *Robotics and Computer-Integrated Manufacturing*, **1**, 97 – 113.

HOGAN, N. (1985). Impedance control: An approach to manipulation, part i - theory, part ii - implementation, part iii - applications. *Journal of Dynamic Systems Measurement and Control*, **107**, 1–7.

HOGAN, N. (1987). Beyond regulators: Modelling control systems as physical systems. In *American Control Conference*, 1468 –1477.

HONG, J., LAFFERRIERE, G., MISHRA, B. & TAN, X. (1990). Fine manipulation with multifinger hands. In *IEEE International Conference on Robotics and Automation*, vol. 3, 1568 –1573.

HONGCAI, Z. & LAN, L. (2010). Sliding mode control on the position for a multifingered hand. In *International Conference on Computer Science and Education (ICCSE)*, 1287 –1290.

HOWE, R., KAO, I. & CUTKOSKY, M. (1988). The sliding of robot fingers under combined torsion and shear loading. In *IEEE International Conference on Robotics and Automation*, vol. 1, 103 –105.

HUNT, K., SAMUEL, A. & MCAREE, P. (1991). Special Configurations of Multi-finger Multi- freedom Grippers - A Kinematic Study. *The International Journal of Robotics Research*, **10**, 123–134.

HYON, S.H., HALE, J. & CHENG, G. (2007). Full-body compliant human-humanoid interaction: Balancing in the presence of unknown external forces. *IEEE Transactions on Robotics*, **23**, 884 –898.

IBERALL, T., JACKSON, J., LABBE, L. & ZAMPANO, R. (1988). Knowledge-based prehension: capturing human dexterity. In *IEEE International Conference on Robotics and Automation*, vol. 1, 82 –87.

J. SHI, N.B., H. LIU (2008). Robust control of robotic manipulators based on integral sliding mode. In *International Journal of Control*, vol. 81, 1537–1548 vol.81.

JACOBSEN, S., WOOD, J., KNUTTI, D. & BIGGERS, K. (1984). The Utah/M.I.T. dextrous hand: Work in progress. **3**, 21–50.

JALANI, J., HERRMANN, G. & MELHUISH, C. (2010). Robust trajectory following for underactuated robot fingers. In *UKACC International Conference on CONTROL 2010*, 495–500.

JALANI, J., HERRMANN, G. & MELHUISH, C. (2011a). Robust active compliance control for practical grasping of a cylindrical object via a multifingered robot hand. In *IEEE Conference on Robotics, Automation and Mechatronics (RAM), 2011*, 316 –321.

JALANI, J., KHAN, S.G., HERRMANN, G. & MELHUISH, C. (2011b). A novel approach of robust active compliance for robot fingers. In *FIRA RoboWorld Congress'11*, 50–57.

JALANI, J., HERRMANN, G. & MELHUISH, C. (2012). Underactuated fingers controlled by robust and adaptive trajectory following methods. *International Journal of Systems Science*, **0**, 1–13.

JAURA, A., OSMAN, M. & KROUGLICOF, N. (1998). Hybrid compliance control for intelligent assembly in a robot work cell. *International Journal of Production Research*, **36**, 2573–2583.

JIN, M., KANG, S.H. & CHANG, P.H. (2006). A robust compliant motion control of robot with certain hard nonlinearities using time delay estimation. In *IEEE International Symposium on Industrial Electronics*, vol. 1, 311 –316.

JOHAN TEGIN, J.W. (2005). Tactile sensing in intelligent robotic manipulationa review. *The International Journal of Industrial Robot*, **32**, 64–70.

JOHNSON, K.L. (1985). *Contact Mechanics*. Cambridge University Press, Cambridge, Cambridge, UK.

KANEKO, K., KANEHIRO, F., KAJITA, S., YOKOYAMA, K., AKACHI, K., KAWASAKI, T., OTA, S. & ISOZUMI, T. (2002). Design of prototype humanoid robotics platform for HRP. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, 2431 – 2436.

KAREL, C. (2001). *R.U.R.*. Dover Publications Inc.

KATOH, I. (1973). Development of biped walking robot (WABOT-1) in Japanese. *Biomechanics*, **2**, 173–184.

KATOH, I., OHTERU, K., SHIRAI, K. & NARITA, S. (1985). Journal of the robotics society in japan. *Biomechanics*, **3**, 337–338.

KATSURA, S. & OHNISHI, K. (2004). Human cooperative wheelchair for haptic interaction based on dual compliance control. *IEEE Transactions on Industrial Electronics*, **51**, 221 – 228.

KAUSCHKE, M. (1996). Closed form solutions applied to redundant serial link manipulators. *Mathematics and Computers in Simulation*, **41**, 509–516.

KAZEROONI, H., HOUPT, P.K. & SHERIDAN, T.B. (1986). Design method for robust compliant motion for manipulators. In *American Control Conference*, 1897 –1906.

KHALIL, H.K. (1996). *Nonlinear Systems, Second Edition,*. CRC Press, Inc.

KHAN, S., HERRMANN, G., G., A., PIPE & MELHUISH, C. (2010). Safe adaptive compliance control of a humanoid robotic arm with anti-windup compensation and posture control. *International Journal of Social Robotics*, **2**, 305–319.

KHATIB, O. (1987). A unified approach for motion and force control of robot manipulators: The operational space formulation. *IEEE Journal of Robotics and Automation*, **3**, 43 –53.

KHATIB, O. (1995). Inertial properties in robotic manipulation: An object-level framework. *The International Journal of Robotics Research*, **14**, 19–36.

KIM, J., BAEK, J. & PARK, F. (1999). Newton-type algorithms for robot motion optimization. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, vol. 3, 1842 –1847.

KIM, J.Y., PARK, I.W., LEE, J., KIM, M.S., KYU CHO, B. & OH, J.H. (2005). System design and dynamic walking of humanoid robot KHR-2. In *IEEE International Conference on Robotics and Automation (ICRA)*, 1431 – 1436.

KLEIN, C. (1984). Use of redundancy in the design of robotic systems. *Proc. of the 2th International Symposium of Robotics Research, MIT Press*, 207 – 214.

KOBAYASHI, K. & YOSHIKAWA, T. (2002). Controllability of Under-Actuated Planar Manipulators with One Unactuated Joint. *The International Journal of Robotics Research*, **21**, 555–561.

KONDO, S. (1988). Force(torque) sensor for robot using vibrating wire. In *Proceeding of the First Robot Sensor Symposium*, 97–100.

KORN, G.A. & KORN, T.M. (1968). *Mathematical Handbook for Scientists and Engineers*. New York: McGraw-Hill.

KOSHKOUEI, A.J. & BURNHAM, K.J. (2006). Integration of active and passive compliance control for safe human-robot coexistence. In *IEEE International Conference on Robotics and Automation, Coventry*, 213–218.

KUGI, A., OTT, C., ALBU-SCHAFFER, A. & HIRZINGER, G. (2008). On the passivity-based impedance control of flexible joint robots. *IEEE Transactions on Robotics*, **24**, 416 –429.

KURIBAYASHI, K., SHIMIZU, S., YUZAWA, T. & TANIGUCHI, T. (1993). A new robot finger force sensor using neural network. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, vol. 1, 217–222.

KVRGIC, V. (1996). Computing of the sub-optimal grasping forces for manipulation of a rough object by multifingered robot hand. In *IEEE International Conference on Robotics and Automation*, vol. 2, 1801 –1806.

LANE, D., DAVIES, J., CASALINO, G., BARTOLINI, G., CANNATA, G., VERUGGIO, G., CANALS, M., SMITH, C., O'BRIEN, D., PICKETT, M., ROBINSON, G., JONES, D., SCOTT, E., FERRARA, A., ANGELLETI, D., COCCOLI, M., BONO, R., VIRGILI, P., PALLAS, R. & GRACIA, E. (1997). Amadeus: advanced manipulation for deep underwater sampling. *Robotics Automation Magazine, IEEE*, **4**, 34 –45.

LANZON, A. & RICHARDS, R. (1999). Trajectory/force control for robotic manipulators using sliding-mode and adaptive control. In *American Control Conference*, vol. 3, 1940 –1944.

LEE, C. & GONZALEZ, R. (2008a). Fuzzy logic versus a PID controller for position control of a muscle-like actuated arm. *Journal of Mechanical Science and Technology*, **22**, 1475–1482.

LEE, C. & GONZALEZ, R. (2008b). Fuzzy logic versus a PID controller for position control of a muscle-like actuated arm. *Journal of Mechanical Science and Technology*, **22**, 1475–1482.

LEE, M. & NICHOLLS, H. (1999). Review article tactile sensing for mechatronicsa state of the art survey. *Mechatronics*, **9**, 1 – 31.

LEE, S.W. & KAMPER, D.G. (2009). Modeling of multiarticular muscles: Importance of inclusion of tendonpulley interactions in the finger. In *IEEE Transactions on Biomedical Engineering*, vol. 56, 2253–2262.

LI, L., ZHU, Q. & XU, L. (2007). Solution for forward kinematics of 6-DOF parallel robot based on particle swarm optimization. In *International Conference on Mechatronics and Automation*, 2968 –2973.

LI, Y. & KAO, I. (2001). A review of modeling of soft-contact fingers and stiffness control for dextrous manipulation in robotics. In *IEEE International Conference on Robotics and Automation (ICRA)*, vol. 3, 3055 – 3060.

LI, Z. & CANNY, J. (1990). Motion of two rigid bodies with rolling constraint. vol. 6, 62 –72.

LIN, C.H., JAN, S.S. & HSIAO, F.B. (2011). Autonomous hovering of an experimental unmanned helicopter system with proportional-integral sliding mode control. **24**, 338–348.

LIU, G., GOLDENBERG, A. & ZHANG, Y. (2004). Precise slow motion control of a direct-drive robot arm with velocity estimation and friction compensation. *Mechatronics*, **14**, 821 – 834.

LIU, T. & WANG, M. (2009). Passive force analysis with elastic contacts for fixturing and grasping. In *IEEE International Conference on Robotics and Automation*, 1691 –1696.

LUH, J., WALKER, M. & PAUL, R. (1980). Resolved-acceleration control of mechanical manipulators. *IEEE Transactions on Automatic Control*, **25**, 468 – 474.

LUO, M., HUANG, Q. & ZHANG, T. (2007). A mathematical model of six-axis force/moment sensor and its applied control method for robot finger. In *IEEE International Conference on Robotics and Biomimetics*, 1960–1965.

MAHINDRIKAR, A., RAO, S. & BANAVAR, R. (2006). Point-to-point control of a 2R planar horizontal underactuated manipulator. vol. 41, 838–844.

MAPLESOFT (2008). Maplesoft. `http://www.maplesoft.com/`.

MARKENSCOFF, X. & PAPADIMITRIOU, C.H. (1989). Optimum grip of a polygon. *The International Journal of Robotics Research*, **8**, 17–29.

MARTON, L. & LANTOS, B. (2007). Modeling, identification, and compensation of stick-slip friction. *IEEE Transactions on Industrial Electronics*, **54**, 511 –521.

MASON, M. & SALISBURY, J.K. (1985). *Robot Hands and the Mechanics of Manipulation*. MIT Press, Cambridge, MA.

MATHWORKS (1984). Mathworks. `http://www.mathworks.com/`.

MAX MENG, Q. (1995). Comparison study of model-based and non-model-based robot controllers. In *IEEE International Conference on Systems, Man and Cybernetics, Intelligent Systems for the 21st Century.*, vol. 1, 61 –66.

MAXON (2010). Maxon. `http://www.maxonmotor.com/`.

MEI, Z.Q., XUE, Y.C. & YANG, R.Q. (2006). Nonlinear friction compensation in mechatronic servo systems. *The International Journal of Advanced Manufacturing Technology*, **30**, 693–699.

MENZEL, R., K.WOELFL & PFEIFFER, F. (1994). Grasping with a dexterous robot hand. *Proceeding on IFAC Symposium of Robot Control*, 303308.

MONTANA, D. (1988). The kinematics of contact and grasp. *The International Journal of Robotics Research*, **7**, 17–32.

MONTANA, D. (1992). Contact stability for two-fingered grasps. *IEEE Transactions on Robotics and Automation*, **8**, 421 –430.

MONTANA, D. (1995a). The kinematics of contact and grasp. *International Journal Robotics Research*, **8**, 421–430.

MONTANA, D. (1995b). The kinematics of multi-fingered manipulation. In *IEEE Transactions on Robotics and Automation*, vol. 11, 491 –503.

MORITA, T., IWATA, H. & SUGANO, S. (1999). Development of human symbiotic robot: Wendy. In *IEEE International Conference on Robotics and Automation*, vol. 4, 3183 – 3188.

MOURI, K., TERASHIMA, K., MINYONG, P., KITAGAWA, H. & MIYOSHI, T. (2007). Identification and hybrid impedance control of human skin muscle by multi-fingered robot hand. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2895 –2900.

MURRAY, R.M., LI, Z. & SASTRY, S.S. (1994). *A mathematical introduction to robotic manipulation*. CRC Press.

NAKAJIMA, S. (1985). Robot ”fanuc man”(in japanese). *Journal of the Robotics Society in Japan*, **3**, 383–384.

NAPIER, J.R. (1956). The prehensile movements of the human hand. *Surger*, **38-B**, 902–13.

NEGASH, D. & MITRA, R. (2010). Integral sliding mode controller for trajectory tracking control of stewart platform manipulator. In *International Conference on Industrial and Information Systems (ICIIS)*, 650 –654.

NEO, E.S., SAKAGUCHI, T. & YOKOI, K. (2008). A humanoid robot that listens, speaks, sees and manipulates in human environments. In *IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*, 419–425.

NGUYEN, V.D. (1988). Constructing force- closure grasps. *The International Journal of Robotics Research*, **7**, 3–16.

NISHIMURA, M. (1929). *Gakutensoku*. Wikipedia.

OHUE, T. (1991). Universal force-moment sensors. In *Journal of the Robotics Society of Japan*, vol. 9, 914–915.

OKADA, M., NAKAMURA, Y. & HOSHINO, S. (2000). Design of active/passive hybrid compliance in the frequency domain-shaping dynamic compliance of humanoid shoulder mechanism. In *IEEE International Conference on Robotics and Automation*, vol. 3, 2250 –2257.

OKADA, T. (1979). Object-handling system for manual industry. *IEEE Transactions on Systems, Man and Cybernetics*, **9**, 79 –89.

OTT, C., ALBU-SCHAFFER, A., KUGI, A., STAMIGIOLI, S. & HIRZINGER, G. (2004). A passivity based cartesian impedance controller for flexible joint robots - part i: torque feedback and gravity compensation. In *IEEE International Conference on Robotics and Automation (ICRA)*, vol. 3, 2659 – 2665.

OTT, C., EIBERGER, O., FRIEDL, W., BAUML, B., HILLENBRAND, U., BORST, C., ALBU-SCHAFFER, A., BRUNNER, B., HIRSCHMULLER, H., KIELHOFER, S., KONIETSCHKE, R., SUPPA, M., WIMBOCK, T., ZACHARIAS, F. & HIRZINGER, G. (2006). A humanoid two-arm system for dexterous manipulation. In *IEEE-RAS International Conference on Humanoid Robots*, 276 –283.

PARK, Y.L., CHAU, K., BLACK, R. & CUTKOSKY, M. (2007). Force sensing robot fingers using embedded fiber bragg grating sensors and shape deposition manufacturing. In *Robotics and Automation, 2007 IEEE International Conference on*, 1510–1516.

PAUL, R. (1987). Problems and research issues associated with the hybrid control of force and displacement. In *IEEE International Conference on Robotics and Automation*, vol. 4, 1966 – 1971.

PAUL, R.P., XU, Y. & YUN, X. (1988). Terminal link force and position control of robot manipulator. In *Theory and Practice of Robots and Manipulators*, MIT Press.

PERRUQUETTI, W. & BARBOT, J.P. (2002). *Sliding Mode Control in Engineering*. John Wiley and Sons, Inc.

PONCE, J. & FAVERJON, B. (1991). On computing three-finger force-closure grasps of polygonal objects. In *Fifth International Conference on Advanced Robotics, Robots in Unstructured Environments (ICAR)*, vol. 2, 1018 –1023.

RADKHAH, K., HEMKER, T., FRIEDMANN, M. & VON STRYK, O. (2009). Towards the deployment of industrial robots as measurement instruments - an extended forward kinematic model incorporating geometric and nongeometric effects. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 124 –129.

RAIBERT, M.H. & CRAIG, J.J. (1981). Hybrid position/force control of manipulators. *Journal of Dynamic Systems, Measurement, and Control*, **103**, 126–133.

REULEAUX, F. (1876). *The Kinematics of Machinery*. Macmillan, 1876,Republished by Dover, NY, 1963.

ROBERTS, R., PAUL, R. & HILLBERRY, B. (1985). The effect of wrist force sensor stiffness on the control of robot manipulators. In *IEEE International Conference on Robotics and Automation*, vol. 2, 269 – 274.

RYAN, E.P. & CORLESS, M. (1984). Ultimate boundedness and asymptotic stability of a class of uncertain dynamical systems via continuous and discontinuous feedback control. *IMA Journal of Mathematical Control and Information*, **1**, 223–242.

SAKAGAMI, Y., WATANABE, R., AOYAMA, C., MATSUNAGA, S., HIGAKI, N. & FUJIMURA, K. (2002). The intelligent asimo: system overview and integration. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, 2478 – 2483.

SALISBURY, J.K. (1980). Active stiffness control of a manipulator in cartesian coordinates. In *IEEE Conference on Decision and Control including the Symposium on Adaptive Processes*, vol. 19, 95 –100.

SATOSHI UEKI, H.K. & MOURI, T. (2009). Adaptive coordinated control of multi-fingered robot hand. In *Journal of Robotics and Mechatronics*, vol. 21, 36–37 vol.1.

SCHIAVI, R., BICCHI, A. & FLACCO, F. (2009). Control of DC motors using proportional integral sliding mode. In *Proceedings of eighteenth International Conference on Systems Engineering*, 259 –264.

SCHLEGL, T. & BUSS, M. (1998). Hybrid closed-loop control of robotic hand regrasping. In *IEEE International Conference on Robotics and Automation*, vol. 4, 3026 –3031.

SCHRAKE, H., RIESELER, H. & F., W. (1990). Symbolic kinematics inversion of redundant robots. *Proceeding of 4th International Symposium Foundations of Robotics, Holzhau*.

SCIAVICCO, L. & SICILIANO, B. (1987). A dynamic solution to the inverse kinematic problem for redundant manipulators. In *IEEE International Conference on Robotics and Automation*, vol. 4, 1081 – 1087.

SENSINGER, J.W. & WEIR, R.F. (2006). Improvements to series elastic actuators. In *IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications*, 1 –7.

S.G. GOODHART, D.J., K.J. BURNHAM (1992). Self-tuning control of non-linear plant - a bilinear approach. In *Transactions of the Institute of Measurement and Control*, vol. 14, 227–232.

SHADOWROBOT (2003). Design of a dextrous hand for advanced CLAWAR applications. In *Proceedings of CLAWAR*, 691–698.

SHIMOGA, K. & GOLDENBERG, A. (1996). Soft robotic fingertips. *The International Journal of Robotics Research*, **15**, 320–334.

SHIMOJO, M. & ISHIKAWA, M. (1993). An active touch sensing method using a spatial filtering tactile sensor. In *IEEE International Conference on Robotics and Automation*, vol. 1, 948 –954.

SHIN, K.G. & LEE, C.P. (1985). Compliant control of robotic manipulators with resolved acceleration. In *IEEE Conference on Decision and Control*, vol. 24, 350 –357.

SINHA, P. & ABEL, J. (1992). A contact stress model for multifingered grasps of rough objects. *IEEE Transactions on Robotics and Automation*, **8**, 7 –22.

SLOTINE, J.J. & SASTRY, S.S. (1983). Tracking control of non-linear systems using sliding surfaces, with application to robot manipulators. *International Journal of Control*, **38**, 465–492.

SLOTINE, J.J.E. & LI, W. (1991). *Applied nonlinear control*. Prentice-Hall, Inc.

SMITH, J.R. (2011). Electric-field sensors.

SNIJDERS, C., VLEEMING, A. & STOECKART, R. (1993). Transfer of lumbosacral load to iliac bones and legs: Part 1: Biomechanics of self-bracing of the sacroiliac joints and its significance for treatment and exercise. *Clinical Biomechanics*, **8**, 285 – 294.

SOMOFF, P. (1900). Über Gebiete von Schraubengeschwindigkeiten eines festen Körpers bei Verschiedener Zahl von Stützflächen. *Zeitschrift für Mathematic and Physik*, **45**, 245306.

SPIERS, A., HERRMANN, G., MELHUISH, C., PIPE, T. & LENZ, A. (2009). Robotic implementation of realistic reaching motion using a sliding mode/operational space controller. In *Advances in Robotics*, vol. 5744, 230–238.

SPIERS, A., HERRMANN, G. & MELHUISH, C. (2010). An optimal sliding mode controller applied to human motion synthesis with robotic implementation. In *American Control Conference (ACC)*, 991 –996.

SPONG, M.W. & VIDYASAGAR, M. (1989). *Robot Dynamics and Control*. John Wiley and Sons, Inc.

SPURGEON, S.K. & DAVIES, R. (1993). A nonlinear control strategy for robust sliding mode performance in the presence of unmatched uncertainty. *International Journal of Control*, **57**, 1107–1123.

SU, C.Y., STEPANENKO, Y. & LEUNG, T.P. (1995). Combined adaptive and variable structure control for constrained robots. *Automatica*, **31**, 483 – 488.

SUGANO, S., TANAKA, Y., OOKA, T. & KATOH., I. (1985). Journal of the robotics society in japan. *Biomechanics*, **3**, 337–338.

SUGIYAMA, S., KOEDA, M., FUJIMOTO, H. & YOSHIKAWA, T. (2009). Measurement of grasp position by human hands and grasp criterion for two soft-fingered robot hands. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2487 –2492.

TACHI, A., ARAI, H. & MAEDA, T. (1989). Development of anthropomorphic teleexistence slave robot. *In Proceedings of the International Conference on Advanced Mechatronics*, **3**, 385–390.

TANG, W.S. & WANG, J. (2002). A Lagrangian network for multifingered hand grasping force optimization. In *International Joint Conference on Neural Networks*, vol. 1, 177–182.

TAROKH, M. & KIM, M. (2007). Inverse kinematics of 7-DOF robots and limbs by decomposition and approximation. In *IEEE Transactions on Robotics*, vol. 23, 595–600.

THAYER, N. & PRIYA, S. (2011). Design and implementation of a dexterous anthropomorphic robotic typing (DART) hand. *Smart Materials and Structures*, **20**, 035010.

TOMEI, P. (1991). A simple PD controller for robots with elastic joints. *IEEE Transactions on Automatic Control*, **36**, 1208 –1213.

TSUJI, T., ACHMAD, J. & MAKOTO, K. (1996). Multi-point impedance control for redundant manipulators. *IEEE Transactions on Systems, Man, Cybernetics-Part B: Cybernetics*, **26**, 707–717.

TSUJIUCHI, N., UEYAMA, H., KOIZUMI, T. & IWASAKI, M. (2003). Grasp control using compliance control with variable stiffness matrix. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, vol. 4, 3294 – 3299.

UTKIN, V. (1977). Variable structure systems with slidings. *IEEE Transactions on Automatic Control*, **2**, 212–222.

UTKIN, V. & LEE, H. (2006). Chattering problem in sliding mode control systems. In *International Workshop on Variable Structure Systems*, 346 –350.

UTKIN, V. & SHI, J. (1996). Integral sliding mode in systems operating under uncertainty conditions. *Proceedings of the 35th IEEE on Decision and Control*, **4**, 4591–4596.

UTKIN, V.I. (1992). *Sliding Modes in Optimization and Control,*. Springer-Verlag, New York.

VANDEWEGHE, J., M.ROGERS, M.WEISSERT & MATSUOKA, Y. (2004). The ACT hand: Design of the skeletal structure. In *IEEE International Conference on Robotics and Automation (ICRA)*.

VINCE, D. (1945). *Android*. Wikipedia.

VON ZITZEWITZ, J., RAUTER, G., VALLERY, H., MORGER, A. & RIENER, R. (2010). Forward kinematics of redundantly actuated, tendon-based robots. In *International Conference on Intelligent Robots and Systems (IROS)*, 2289 –2294.

WALKER, I. (1990). The use of kinematic redundancy in reducing impact and contact effects in manipulation. In *IEEE International Conference on Robotics and Automation*, vol. 1, 434 –439.

WANG, B., JIANG, L., LI, J. & CAI, H. (2005). Grasping unknown objects based on 3D model reconstruction. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 461 –466.

WANG, W., LOH, R.N. & GU, E.Y. (1998). Passive compliance versus active compliance in robot-based automated assembly systems. *Industrial Robot: An International Journal*, **25**, 48 – 57.

WANG, Y., KUMAR, V. & ABEL, J. (1992). Dynamics of rigid bodies with multiple frictional contacts. *IEEE International Conference on Robotics and Automation*.

WASLANDER, S., HOFFMANN, G., JANG, J.S. & TOMLIN, C. (2005). Multi-agent quadrotor testbed control design: integral sliding mode vs. reinforcement learning. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 3712 – 3717.

WHITNEY, D.E. (1977). Force feedback control of manipulator fine motions. *Journal of Dynamic Systems, Measurement, and Control*, **99**, 91–97.

WOLFRAM, S. (1999). *The Mathematica Book*. Addison-Wesley Publishing Company, 4th edn.

WU, C. & PAUL, R.P. (1980). Manipulator compliance based on joint torque control. In *IEEE Conference on Decision and Control including the Symposium on Adaptive Processes*, vol. 19, 88 –94.

XIE, W.F. (2007). Sliding-mode-observer-based adaptive control for servo actuator with friction. *IEEE Transactions on Industrial Electronics*,, **54**, 1517 –1527.

XU, J., WANG, M., WANG, H. & LI, Z. (2007). Force analysis of whole hand grasp by multifingered robotic hand. In *IEEE International Conference on Robotics and Automation*, 211 –216.

XU, Y. & PAUL, R. (1988). On position compensation and force control stability of a robot with a compliant wrist. In *IEEE International Conference on Robotics and Automation*, vol. 2, 1173 –1178.

XU, Y. & PAUL, R. (1990). A robot compliant wrist system for automated assembly. In *IEEE International Conference on Robotics and Automation*, vol. 3, 1750 –1755.

XYDAS, N. & KAO, I. (1999). Modeling of contact mechanics and friction limit surfaces for soft fingers in robotics, with experimental results. vol. 18, 941–950.

YAGIZ, N., ARSLAN, Y.Z. & HACIOGLU, Y. (2007). Sliding Mode Control of a Finger for a Prosthetic Hand. *Journal of Vibration and Control*, **13**, 733–749.

YAMAZAKI, Y., INOUE, T. & HIRAI, S. (2009). Two-phased force and coordinates controller for a pair of 2-DOF soft fingers. In *IEEE International Conference on Robotics and Biomimetics*, 931 –937.

YOKOYAMA, M., KIM, G.N. & TSUCHIYA, M. (2010). Integral Sliding Mode Control with Anti-windup Compensation and Its Application to a Power Assist System. In *Journal of Vibration and Control*, vol. 16, 503–512.

YOSHIDA, M., ARIMOTO, S. & LUO, Z.W. (2008). Three-dimensional object manipulation by two robot fingers with soft tips and minimum D.O.F. In *IEEE International Conference on Robotics and Automation*, 1615 –1621.

YOSHIKAWA, T. (1985). Manipulability and redundancy control of robotic mechanisms. *Proceeding IEEE International Conference on Robotics and Automation*, 1004–1009.

YOSHIKAWA, T. (1996). Passive and active closures by constraining mechanisms. In *Proceedings IEEE International Conference on Robotics and Automation*, vol. 2, 1477 –1484.

YOSHIKAWA, T., KOEDA, M. & FUJIMOTO, H. (2008). Shape recognition and grasping by robotic hands with soft fingers and omnidirectional camera. In *IEEE International Conference on Robotics and Automation (ICRA)*, 299 –304.

YOUNG, K., UTKIN, V. & OZGUNER, U. (1996). A control engineer's guide to sliding mode control. In *IEEE International Workshop on Variable Structure Systems*, 1 –14.

YU, X. & KAYNAK, O. (2009). Sliding-mode control with soft computing: A survey. *IEEE Transactions on Industrial Electronics*, **56**, 3275 –3285.

YUSSOF, H., OHKA, M., SUZUKI, H. & MORISAWA, N. (2008). Tactile sensing-based control algorithm for real-time grasp synthesis in object manipulation tasks of humanoid robot fingers. In *IEEE International Symposium on Robot and Human Interactive Communication*, 377–382.

ZHANG, W., CHEN, Q., SUN, Z. & ZHAO, D. (2003). Under-actuated passive adaptive grasp humanoid robot hand with control of grasping force. In *IEEE International Conference on Robotics and Automation (ICRA)*, vol. 1, 696 – 701.

ZHANG, W., CHEN, Q., SUN, Z. & ZHAO, D. (2004). Passive adaptive grasp multi-fingered humanoid robot hand with high under-actuated function. In *IEEE International Conference on Robotics and Automation (ICRA)*, vol. 3, 2216–2221.

ZHANG, Y. & WANG, J. (2004). Obstacle avoidance for kinematically redundant manipulators using a dual neural network. *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, **34**, 752 – 759.

ZINK, A. & KYRIAKOPOULOS, K. (1993). Dynamic modeling and force/position control for the anthrobot dextrous robotic hand. In *IEEE Conference on Decision and Control*, vol. 3, 2682 –2687.