Contents

Lis	List of Abbreviations LI		
	trodu		
Вr	uno Si	ciliano, Oussama Khatib	1
Pā	art A	Robotics Foundations	
1 Kinematics			
	Kenn	eth Waldron, James Schmiedeler	9
	1.1	Overview	9
	1.2	Position and Orientation Representation	10
	1.3	Joint Kinematics	18
	1.4	Geometric Representation	23
	1.5	Workspace	25
	1.6	Forward Kinematics	26
	1.7	Inverse Kinematics	27
	1.8	Forward Instantaneous Kinematics	29
	1.9	Inverse Instantaneous Kinematics	30
	1.10	Static Wrench Transmission	30
	1.11	Conclusions and Further Reading	31
	Refer	ences	31
2	Dyna	mics	
	Roy F	eatherstone, David E. Orin	35
	2.1	Overview	36
	2.2	Spatial Vector Notation	37
	2.3	Canonical Equations	43
	2.4	Dynamic Models of Rigid-Body Systems	45
	2.5	Kinematic Trees	50
	2.6	Kinematic Loops	57
	2.7	Conclusions and Further Reading	60
	Refer	ences	62
3	Mech	nanisms and Actuation	
	Victor	Scheinman, J. Michael McCarthy	67
	3.1	Overview	67
	3.2	System Features	68
	3.3	Kinematics and Kinetics	69
	3.4	Serial Robots	72
	3.5	Parallel Robots	73
	3.6	Mechanical Structure	75

	7.5	Conclusions and Further Reading	181			
	Refer	ences	183			
8	Robotic Systems Architectures and Programming					
Ü		Kortenkamp, Reid Simmons	187			
	8.1	Overview	187			
	8.2	History	189			
	8.3	Architectural Components	193			
	8.4	Case Study – GRACE	200			
	8.5	The Art of Robot Architectures	202			
	8.6	Conclusions and Further Reading	203			
	Refer	ences	204			
9		asoning Methods for Robotics	207			
		im Hertzberg, Raja Chatila	207			
	9.1	Knowledge Representation and Inference	208			
	9.2	KR Issues for Robots	212			
	9.3	Action Planning	214			
	9.4	Robot Learning	219			
	9.5	Conclusions and Further Reading	221			
	Keier	ences	222			
Pā	rt B	Robot Structures				
10	Perfo	rmance Evaluation and Design Criteria				
10		Angeles, Frank C. Park	229			
	10.1		229			
	10.2	Workspace Criteria	231			
	10.3	Dexterity Indices	235			
	10.4	Other Performance Indices	238			
		ences	242			
11		natically Redundant Manipulators				
	Stefar	no Chiaverini, Giuseppe Oriolo, Ian D. Walker	245			
	11.1		245			
	11.2					
	11.2	Task-Oriented Kinematics	247			
	11.3	Task-Oriented Kinematics	250			
	11.3 11.4	Task-Oriented Kinematics	250 255			
	11.3 11.4 11.5	Task-Oriented Kinematics Inverse Differential Kinematics Redundancy Resolution via Optimization Redundancy Resolution via Task Augmentation	250 255 256			
	11.3 11.4 11.5 11.6	Task-Oriented Kinematics Inverse Differential Kinematics Redundancy Resolution via Optimization Redundancy Resolution via Task Augmentation Second-Order Redundancy Resolution	250 255 256 259			
	11.3 11.4 11.5 11.6 11.7	Task-Oriented Kinematics Inverse Differential Kinematics Redundancy Resolution via Optimization Redundancy Resolution via Task Augmentation Second-Order Redundancy Resolution Cyclicity	250 255 256 259 260			
	11.3 11.4 11.5 11.6 11.7 11.8	Task-Oriented Kinematics Inverse Differential Kinematics Redundancy Resolution via Optimization Redundancy Resolution via Task Augmentation Second-Order Redundancy Resolution Cyclicity Hyperredundant Manipulators	250 255 256 259 260 261			
	11.3 11.4 11.5 11.6 11.7 11.8 11.9	Task-Oriented Kinematics Inverse Differential Kinematics Redundancy Resolution via Optimization Redundancy Resolution via Task Augmentation Second-Order Redundancy Resolution Cyclicity	250 255 256 259 260			

12	Parall	lel Mechanisms and Robots	
	Jean-l	Pierre Merlet, Clément Gosselin	269
	12.1	Definitions	269
	12.2	Type Synthesis of Parallel Mechanisms	271
	12.3	Kinematics	271
	12.4	Velocity and Accuracy Analysis	273
	12.5	Singularity Analysis	274
	12.6	Workspace Analysis	276
	12.7	Static Analysis and Static Balancing	277
	12.8	Dynamic Analysis	279
	12.9	Design	279
	12.10	Application Examples	280
	12.11	Conclusion and Further Reading	281
	Refere	ences	281
		ts with Flexible Elements	
		ndro De Luca, Wayne Book	287
	13.1	Robots with Flexible Joints	288
	13.2	Robots with Flexible Links	306
	Refere	ences	317
1/	Modo	I Identification	
			321
	14.1	Hollerbach, Wisama Khalil, Maxime Gautier	321
	14.2	Kinematic Calibration	323
	14.3	Inertial Parameter Estimation	330
	14.4	Identifiability and Numerical Conditioning	334
	14.5	Conclusions and Further Reading	341
		ences	342
	Kerere	inces	J+2
15	Robot	t Hands	
	Claudi	o Melchiorri, Makoto Kaneko	345
	15.1	Basic Concepts	346
	15.2	Design of Robot Hands	347
	15.3	Technologies for Actuation and Sensing	351
	15.4	Modeling and Control of a Robot Hand	355
	15.5	Applications and Trends	359
	15.6	Conclusions and Further Reading	359
	Refere	ences	359
		ed Robots	
		Kajita, Bernard Espiau	361
	16.1	A Brief History	362
	16.2	Analysis of Cyclic Walking	363
	16.3	Control of Biped Robots Using Forward Dynamics	366
	16.4	Biped Robots in the ZMP Scheme	371
	16.5	Multilegged Robots	378

	20.7	Further Reading	489
	20.8	Currently Available Hardware	489
	Refere	nces	490
21	Sonar	Sensing	
	Lindsa	ıy Kleeman, Roman Kuc	491
	21.1	Sonar Principles	492
	21.2	Sonar Beam Pattern	494
	21.3	Speed of Sound	496
	21.4	Waveforms	496
	21.5	Transducer Technologies	497
	21.6	Reflecting Object Models	499
	21.7	Artifacts	500
	21.8	TOF Ranging	501
	21.9	Echo Waveform Coding	503
	21.10	Echo Waveform Processing	506
	21.11	CTFM Sonar	508
	21.12	Multipulse Sonar	511
	21.13	Sonar Rings	512
	21.14	Motion Effects	513
		Biomimetic Sonars	515
	21.16	Conclusions	516
	Refere	nces	517
22	Robert 22.1 22.2 22.3	Navigation and Terrain Classification	521 521 530 537
	22.4	Conclusions and Further Reading	540
	Refere	nces	540
23	3-D V	ision and Recognition	
		Daniilidis, Jan-Olof Eklundh	543
		3-D Vision and Visual SLAM	544
		Recognition	551
		Conclusion and Further Reading	558
		nces	559
24		Servoing and Visual Tracking	
		ois Chaumette, Seth Hutchinson	563
	24.1	The Basic Components of Visual Servoing	564
	24.2	Image-Based Visual Servo	565
	24.3	Position-Based Visual Servo	572
	24.4	Advanced Approaches	574
	24.5	Performance Optimization and Planning	577
	24.6	Estimation of 3-D Parameters	578

		Conclusion and Further Reading	697 698			
	Kelele	inces	030			
29	Coope	Cooperative Manipulators				
		io Caccavale, Masaru Uchiyama	701			
	29.1	A Historical Overview	701			
	29.2	Kinematics and Statics	703			
	29.3	Cooperative Task Space	707			
	29.4	Dynamics and Load Distribution	708			
	29.5	Task-Space Analysis	710			
	29.6	Control	711			
	29.7	Conclusions and Further Reading	715			
		_	716			
	Kelele	nces	110			
30	Hapti	rs				
50	-	Hannaford, Allison M. Okamura	719			
	30.1	Overview	719			
	30.2	Haptic Device Design	724			
	30.3	Haptic Rendering	727			
	30.4	Control and Stability of Haptic Interfaces	730			
	30.4	Tactile Display	731			
	30.5		735			
		Conclusions and Further Reading				
	Keiere	nces	735			
31	Telero	botics				
J <u>.</u>		r Niemeyer, Carsten Preusche, Gerd Hirzinger	741			
	31.1		741			
	31.2	Telerobotic Systems and Applications	743			
	31.3	Control Architectures	746			
	31.4	Bilateral Control and Force Feedback	751			
	31.5		754			
		· · · · · · · · · · · · · · · · · · ·				
	кетеге	nces	755			
32	Networked Telerobots					
_		n Song, Ken Goldberg, Nak Young Chong	759			
		Overview and Background	759			
		A Brief History	760			
		Communications and Networking	761			
	32.4	Conclusion and Future Directions	769			
		ences	769			
	Kerere		103			
33	Exosk	eletons for Human Performance Augmentation				
	Homayoon Kazerooni					
	33.1	Survey of Exoskeleton Systems	773 773			
	33.2	Upper-Extremity Exoskeleton	775			
	33.3	Intelligent Assist Device	776			
		Control Architecture for Upper-Extremity Exoskeleton Augmentation	778			

	33.5	Applications of Intelligent Assist Device	780
	33.6	Lower-Extremity Exoskeleton	780
	33.7	The Control Scheme of an Exoskeleton	782
	33.8	Highlights of the Lower-Extremity Design	786
	33.9	Field-Ready Exoskeleton Systems	790
	33.10	Conclusion and Further Reading	792
		nces	792
D-	ret E I	Mobile and Distributed Robotics	
34		n Control of Wheeled Mobile Robots	700
		Morin, Claude Samson	799
	34.1	Background	800
	34.2	Control Models	801
	34.3	Adaptation of Control Methods for Holonomic Systems	804
	34.4	Methods Specific to Nonholonomic Systems	806
	34.5	Complementary Issues and Bibliographical Guide	823
	Refere	nces	825
35	Motio	n Planning and Obstacle Avoidance	
	Javier	Minguez, Florent Lamiraux, Jean-Paul Laumond	827
	35.1	Nonholonomic Mobile Robots:	
		Where Motion Planning Meets Control Theory	828
	35.2	Kinematic Constraints and Controllability	829
	35.3	Motion Planning and Small-Time Controllability	830
	35.4	Local Steering Methods and Small-Time Controllability	832
	35.5	Robots and Trailers	835
	35.6	Approximate Methods	837
	35.7	From Motion Planning to Obstacle Avoidance	837
	35.8	Definition of Obstacle Avoidance	838
	35.9	Obstacle Avoidance Techniques	839
		Robot Shape, Kinematics, and Dynamics in Obstacle Avoidance	845
		Integration Planning – Reaction	847
		Conclusions, Future Directions, and Further Reading	849
		nces	850
26	Morld	Modeling	
30			0.50
		m Burgard, Martial Hebert	853
	36.1	Historical Overview	854
	36.2	World Models for Indoors and Structured Environments	855
	36.3	World and Terrain Models for Natural Environments	859
	36.4	Dynamic Environments	866
	Ketere	nces	867
37	Simul	taneous Localization and Mapping	
	Sebast	tian Thrun, John J. Leonard	871
	37.1	Overview	871

	37.2	SLAM: Problem Definition	872			
	37.3	The Three Main SLAM Paradigms	875			
	37.4	Conclusion and Future Challenges	885			
	37.5	Suggestions for Further Reading	886			
	Refere	ences	886			
3 0	Roha	vior-Based Systems				
50		J. Matarić, François Michaud	891			
	38.1	Robot Control Approaches	891			
	38.2	Basic Principles of Behavior–Based Systems	894			
	38.3	Basis Behaviors	897			
	38.4	Representation in Behavior-Based Systems	897			
	38.5	Learning in Behavior-Based Systems	898			
	38.6	Continuing Work	902			
	38.7	Conclusions and Further Reading	902			
		ences	905			
	Kelele	:iices	900			
39		buted and Cellular Robots				
	Zack E	Butler, Alfred Rizzi	911			
	39.1	Modularity for Locomotion	911			
	39.2	Modularity for Manipulation	914			
	39.3	Modularity for Geometric Reconfiguration of Robot Systems	915			
	39.4	Modularity for Robustness	918			
	39.5	Conclusions and Further Reading	918			
	Refere	ences	919			
40	Multi	ple Mobile Robot Systems				
		E. Parker	921			
	40.1	History	922			
	40.2	Architectures for Multirobot Systems	922			
	40.3	Communication	925			
	40.4	Swarm Robots	926			
	40.5	Heterogeneity	928			
	40.6	Task Allocation	930			
	40.7	Learning	932			
	40.8	Applications	933			
	40.9	Conclusions and Further Reading	935			
	Refere	ences	936			
<i>I</i> . 1	Nota	orked Pohots				
41		Networked Robots				
	<i>vijay i</i> 41.1	Kumar, Daniela Rus, Gaurav S. Sukhatme	943 943			
	41.1	OverviewState of the Art and Potential	943			
	41.3	Research Challenges	947			
	41.4	Control	949			
	41.5	Communication for Control	950			
	41.6	Communication for Perception	951			

	41.7 41.8	Control for Perception	952 953
	41.9	Conclusions and Further Reading	955
	Refere	ences	955
Pa	rt F	Field and Service Robotics	
42	Indus	strial Robotics	
	Martir	1 Hägele, Klas Nilsson, J. Norberto Pires	963
	42.1	A Short History of Industrial Robots	964
	42.2	Typical Applications and Robot Configurations	969
	42.3	Kinematics and Mechanisms	975
	42.4	Task Descriptions – Teaching and Programming	976
	42.5	End-Effectors and System Integration	980
	42.6	Conclusions and Long-Term Challenges	983
	Refere	ences	985
43	Unde	rwater Robotics	
	Gianlı	uca Antonelli, Thor I. Fossen, Dana R. Yoerger	987
	43.1	The Expanding Role of Marine Robotics in Oceanic Engineering	987
	43.2	Underwater Robotics	989
	43.3	Applications	1003
	43.4	Conclusions and Further Reading	1005
	Refere	ences	1005
44	Aeria	l Robotics	
	Eric Fe	eron, Eric N. Johnson	1009
	44.1	Background	1010
	44.2	History of Aerial Robotics	1010
	44.3	Applications of Aerial Robotics	1012
	44.4	Current Challenges	1014
	44.5	Basic Aerial Robot Flight Concepts	1015
	44.6	The Entry Level for Aerial Robotics: Inner-Loop Control	1020
	44.7	Active Research Areas	
	44.8	Conclusions and Further Reading	
	Refere	ences	1027
45	Space	Robots and Systems	
		a Yoshida, Brian Wilcox	1031
	45.1	Historical Developments and Advances of Orbital Robotic Systems	
	45.2	Historical Developments and Advances of Surface Robotic Systems	
	45.3	Mathematical Modeling	
	45.4	Future Directions of Orbital and Surface Robotic Systems	
	45.5	Conclusions and Further Reading	
		ences	1060

55	Robots for Education			
	David	P. Miller, Illah R. Nourbakhsh, Roland Siegwart	1283	
	55.1	The Role of Robots in Education		
	55.2	Educational Robot Tournaments	1285	
	55.3	Education Robot Platforms		
	55.4	Education Robot Controllers and Programming Environments		
	55.5	Robots and Informal Learning Venues (Museums)	1292	
	55.6	Educational Evaluation of Robot Programs		
	55.7	Conclusions and Further Reading		
		nces		
Pa	rt G	Human-Centered and Life-Like Robotics		
56	Huma	noids		
	Charle	s C. Kemp, Paul Fitzpatrick, Hirohisa Hirukawa, Kazuhito Yokoi,		
	Kensul	ke Harada, Yoshio Matsumoto	1307	
	56.1	Why Humanoids?	1307	
	56.2	History and Overview	1310	
	56.3	Locomotion	1312	
	56.4	Manipulation	1315	
	56.5	Whole-Body Activities		
	56.6	Communication	1325	
	56.7	Conclusions and Further Reading		
	Refere	nces		
57	Safety	for Physical Human–Robot Interaction		
		o Bicchi, Michael A. Peshkin, J. Edward Colgate	1335	
	57.1	Motivations for Safe pHRI		
	57.2	Safety for Hands-Off pHRI		
	57.3	Design of Intrinsically Safe Robots		
	57.4	Safety for Hands-On pHRI		
	57.5	Safety Standards for pHRI		
	57.6	Conclusions		
		nces		
			13.10	
58		Robots that Interact with People		
	Cynthi	a Breazeal, Atsuo Takanishi, Tetsunori Kobayashi	1349	
	58.1	Social Robot Embodiment	1350	
	58.2	Multimodal Communication	1352	
	58.3	Expressive Emotion-Based Interaction	1356	
	58.4	Socio-cognitive Skills	1360	
	58.5	Conclusion and Further Reading	1365	
	Refere	nces	1366	
59	Robot	Programming by Demonstration		
		Billard, Sylvain Calinon, Rüdiger Dillmann, Stefan Schaal	1371	
		History	1372	

Overview1481Example-Based Object Representations1483

	63.3	Example-Based Movement Representations	1490
	63.4	Example-Based Synthesis Models: From Faces to Movements	1492
	63.5	Conclusions and Further Reading	1494
	Refere	nces	1495
64	Roboe	ethics: Social and Ethical Implications of Robotics	
	Gianm	arco Veruggio, Fiorella Operto	1499
	64.1	A Methodological Note	1501
	64.2	Specificity of Robotics	
	64.3	What Is a Robot?	1502
	64.4	Cultural Differences in Robot's Acceptance	1503
	64.5	From Literature to Today's Debate	1503
	64.6	Roboethics	1504
	64.7	Ethics and Morality	1505
	64.8	Moral Theories	1505
	64.9	Ethics in Science and Technology	1506
	64.10	Conditions for Implementation	1507
	64.11	Operativeness of the Principles	1507
	64.12	Ethical Issues in an ICT Society	1507
	64.13	Harmonization of Principles	1509
	64.14	Ethics and Professional Responsibility	1510
	64.15	Roboethics Taxonomy	1511
	64.16	Conclusions and Further Reading	1519
	Refere	nces	1522
Ac	knowle	edgements	1525
		e Authors	1527
De	tailed	Contents	1555
Su	Subject Index		