

Contents

1	Introduction	1
1.1	Why Mastication Robots	1
1.2	The Masticatory System	3
1.2.1	Jaw and Temporomandibular Joint	3
1.2.2	Muscles of Mastication	5
1.2.3	Teeth	6
1.3	Measurement of Mastication Movement	7
1.3.1	Jaw Movement	8
1.3.2	Chewing Forces	10
1.4	Computational Models of the Masticatory System	12
1.4.1	Dynamics Models	12
1.4.2	Kinematics Model	14
1.5	Mastication Robots	15
1.5.1	Dental Training Robot	15
1.5.2	Jaw Simulator	18
1.5.3	Foods Chewing Robot	19
1.5.4	Other Mastication Robots	23
1.6	Computational Intelligence in Mastication	24
1.7	Discussion	26
1.8	Summary	28
	References	28
2	Robotic Models of the Masticatory System	35
2.1	A Mechanism Model of the Masticatory System	35
2.1.1	Jaw Muscles and Movements	35
2.1.2	Jaw Mechanism Modeling	37
2.2	Kinematics Simulations in SimMechanics	39
2.2.1	Physical Quantities of the Mechanism	40
2.2.2	Actuation Modes	41
2.2.3	Results and Analysis	42
2.3	A Robotic Model of the Masticatory System	45
2.3.1	The Robotic Model	45
2.3.2	Physical Quantities of the Model	46
2.4	Kinematics Simulation in SolidWorks/CosmosMotion	49

2.4.1 Forward Kinematics Simulation	50
2.4.2 Inverse Kinematics Simulation	53
2.5 Summary	57
References	58
3 Mastication Robot of Linear Actuation	59
3.1 A Refined Robotic Model	59
3.2 Motion Design of the Actuation	62
3.3 Force Design of the Actuation	65
3.4 Design of the Actuation System	67
3.4.1 Basic Design Requirements	67
3.4.2 Types of Actuation	68
3.4.3 Actuator Control	71
3.4.4 Physical Design	73
3.5 Design of Mastication Robot	85
3.5.1 Actuator Assembly	86
3.5.2 Actuator Mounting	88
3.6 Summary	88
References	89
4 Mastication Robot of Crank Actuation	91
4.1 The 6RSS Parallel Mechanism	91
4.2 Coordinate Systems and Kinematical Parameters	93
4.3 Inverse Kinematics	95
4.4 Singularity Analysis	97
4.5 Design of the Robot	98
4.5.1 Framework Design	98
4.5.2 Lower and Upper Jaw	100
4.6 Motion Control	102
4.7 Simulation in SolidWorks/CosmosMotion	104
4.8 Simulation in SimMechanics	110
4.9 Initial Chewing Experiments	121
4.9.1 Masticatory Movements	121
4.9.2 Robotic Chewing without Food	121
4.9.3 Robotic Chewing of Simulated Foods	124
4.10 Summary	128
References	128
5 Mastication Robot of a Crank-Slider Linkage	129
5.1 Why a Linkage Mechanism for Mastication	129
5.2 Design Specifications	131
5.3 Basic Linkage Mechanism for an Incisor Trajectory	132
5.4 Six-Bar Linkage Mechanism for Jaw Movement	138
5.4.1 The Six-Bar Linkage	138
5.4.2 Motion Planning	139
5.4.3 Motor Selection	141

5.5	Analysis of the Mechanism.....	142
5.5.1	Trajectory and Force Evaluation.....	142
5.5.2	Stress and Deformation.....	143
5.6	Mechanical Design of the Mechanism.....	145
5.6.1	Limiting the Chewing Force.....	145
5.6.2	The Enclosure.....	145
5.6.3	Teeth Locking.....	147
5.6.4	The Teeth and Food Retention System.....	149
5.7	Measurement of the Chewing Force.....	152
5.8	The Control System.....	153
5.8.1	Computer/Motor Interface.....	153
5.8.2	Hall Effect Sensor.....	154
5.8.3	The Software Functions.....	156
5.8.4	Chewing Trajectory Setting.....	156
5.9	Chewing Experiments.....	158
5.9.1	Operation of the Chewing Robot.....	158
5.9.2	Results and Discussion.....	159
5.10	Summary.....	162
	References.....	162
6	Measurement and Reproduction of Mastication Movement	163
6.1	Mastication Measurement.....	163
6.1.1	The Techniques.....	163
6.1.2	The Measurement.....	164
6.2	Coordinate Systems for the Movement.....	165
6.2.1	The Sensor and Mandible Systems.....	165
6.2.2	The Skull System.....	167
6.3	Reproduction of the Movements.....	169
6.4	GUIs for Analysis of the Movements.....	173
6.5	Summary.....	176
	References.....	177
7	Robotic Chewing Experiments	179
7.1	Introduction.....	179
7.2	Force Measurement.....	181
7.3	Experiments for One-DOF Chewing Trajectory.....	184
7.4	Experiments with Two-DOF Chewing Trajectory.....	189
7.5	Experiments with Six-DOF Chewing Trajectory.....	198
7.6	Summary.....	205
	References.....	206
8	Understanding Food Texture Using Masticatory Robots.....	207
8.1	Introduction.....	207
8.2	Specifying a Mastication Robot for Texture Measurement.....	209
8.2.1	Tooth Shape.....	211
8.2.2	Teeth Kinematics.....	211

8.2.3	Control Strategy	212
8.2.4	Sample Size and Manipulation	213
8.2.5	Bolus Retention and Losses	214
8.2.6	Moisture and Temperature Control	215
8.3	Masticatory Robots – Current Capability	216
8.3.1	Waseda Jaws Mastication Robot	216
8.3.2	BITE Master II	217
8.3.3	INRA Flavour Release Chewing Simulator	219
8.3.4	Linkage Mechanism Mastication Robot	222
8.3.5	Six-DOF Parallel Chewing Robot	231
8.3.6	Other Oral Simulation Devices	233
8.4	Summary	234
	References	234
9	Neural Control of a Mastication Robot	237
9.1	Why CPG for Control	237
9.2	Matsuoka Oscillator Fundamentals	239
9.3	Tuning of a Matsuoka Oscillator	241
9.3.1	GUI for Simulation of the Oscillator	241
9.3.2	GUI for Influence of the Oscillator Parameters	243
9.3.3	GUI for Adaptation of the Oscillator	244
9.4	Case Study	248
9.4.1	Purpose and Assumptions	248
9.4.2	Modeling of the Masticatory Muscles	249
9.4.3	Simulations	251
9.5	Hardware-in-the-Loop Simulations	256
9.5.1	Simulation Setup	256
9.5.2	Implementation of the Algorithm	259
9.5.3	Experimental Results	263
9.6	Summary	268
	References	269
10	Knowledge System of Human Chewing Behaviours	271
10.1	The Need for Knowledge Systems	271
10.2	Object-Oriented Knowledge Representation	273
10.2.1	Object-Oriented Model Describing Jaw Physiology	273
10.2.2	Object-Oriented Model for the Chewing Process	274
10.3	Knowledge Discovery	276
10.3.1	Data Mining for Association Rules	276
10.3.2	Object-Oriented Model Describing Inter-property Association	277
10.3.3	Object-Oriented Knowledge Representation	277
10.3.4	Data Pre-processing	279
10.3.5	Implementation	279
10.4	Case Study	280
10.4.1	Attributes of the Chewing Properties	280

10.4.2 Pre-processing of Raw Data for Data Mining	281
10.4.3 Data Mining Results and Their Interpretation	282
10.5 Summary	284
References	284
Appendix	286
Index	289