Advances in Industrial Control

For further volumes:
www.springer.com/series/1412

Pål Liljebäck • Kristin Y. Pettersen •
Øyvind Stavdahl • Jan Tommy Gravdahl

Snake Robots

Modelling, Mechatronics, and Control

Pål Liljebäck
Applied Cybernetics
SINTEF ICT
Trondheim, Norway
and
Department of Engineering Cybernetics
Norwegian University of Science &
Technology
Trondheim, Norway

Kristin Y. Pettersen
Department of Engineering Cybernetics
Norwegian University of Science &
Technology
Trondheim, Norway

Øyvind Stavdahl
Department of Engineering Cybernetics
Norwegian University of Science &
Technology
Trondheim, Norway

Jan Tommy Gravdahl
Department of Engineering Cybernetics
Norwegian University of Science &
Technology
Trondheim, Norway

The following images in the book are used under license from Shutterstock.com:

Image of snake on page 1: Copyright Angel Simon, 2011.

Image in Fig. 1.2b: Copyright RedTC, 2011.

Image in Fig. 1.3: Copyright Srdjan Draskovic, 2011.

Image in Fig. 1.4: Copyright photoBeard, 2011.

Image of snake on page 287: Copyright Steve Bower, 2011.

The following images in the book are used under license from Dreamstime.com:

Images in Fig. 1.5: Copyright Isselee, 2011.

ISSN 1430-9491

Advances in Industrial Control

ISBN 978-1-4471-2995-0

DOI 10.1007/978-1-4471-2996-7

Springer London Heidelberg New York Dordrecht

ISSN 2193-1577 (electronic)

ISBN 978-1-4471-2996-7 (eBook)

Library of Congress Control Number: 2012938883

© Springer-Verlag London 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To our families

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies, . . . , new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

Over the years the *Advances in Industrial Control* series has been very fortunate in publishing monographs that were often seminal for the development of new areas in control systems theory and industrial technology. These monographs were often written by young researchers making their way in the industrial control field or were a report of a substantial research project that was now ready for holistic presentation and dissemination. For a monograph series that spans two decades, it is actually quite easy to find examples of this type of motivational text. From the early years of the series, *Iterative Learning Control for Deterministic Systems* by Kevin L. Moore (ISBN 978-3-540-19707-2, 1992) and *Autotuning of PID Controllers* by Cheng-Ching Yu (ISBN 978-3-540-76250-8, 1999) are good examples. In more recent years we can cite *Control of Fuel Cell Power Systems* by Jay T. Pukrushpan, Anna G. Stefanopoulou, and Huei Peng (ISBN 978-1-85233-816-9, 2004), *Predictive Functional Control* by Jacques Richalet and Donal O'Donovan (ISBN 978-1-84882-492-8, 2009) and finally *Internet-Based Control Systems* by Shuang-Hua Yang (ISBN 978-1-84996-358-9, 2011) as typical *Advances in Industrial Control* monographs that are studied as key texts for their respective topics.

Clearly *Snake Robots* by Pål Liljebäck, Kristin Y. Pettersen, Øyvind Stavdahl, and Jan Tommy Gravdahl is going to be a much read, studied, and cited monograph in this particular field of robot development. After a truly fascinating introductory chapter that examines among other topics, biological snake motion, the monograph is structured into two parts. Part I investigates and reports on modelling, technology, and control for snake robot locomotion in a planar (flat) environment (Chaps. 2–8).

Part II moves on to snake locomotion in a cluttered environment with stationary objects (Chaps. 9–13). This group of chapters introduces and explores the concept of “obstacle-aided” locomotion. So much of mobile robot technology is concerned with obstacle avoidance, so it is interesting to see a robot application that exploits the contact with objects (obstacles) in the environment to *aid* locomotion. The monograph closes with a concluding chapter, three short technical appendices, a useful Glossary of technical terms, and an exhaustive Index.

The authors have succeeded in writing a well-structured text that is both a scientific and an engineering monograph. The structure and contents of the monograph can be accessed in several different ways. For example, the monograph presents mathematical models that elucidate snake motion *per se*; this describes important *fundamental* scientific principles in the field. Alternatively, the monograph can be used as a source for up-to-date survey and review material on snake-robotic engineering and technology; apart from the thorough historical review in Chap. 1, each subsequent chapter opens with a section that creates the context and reviews the past literature relating to the work to be presented by the authors. One of the attractive features of the monograph is the way in which the authors use the chapter sequence to work through increasingly complex issues in the understanding, control and technology of snake robots. Such careful attention to structure allows the expert researcher and the researcher new to the field rapidly to assess the importance of the material presented and its relation to past developments. Finally, the monograph presents the authors' own research and development in the field. This research covers the full spectrum of mathematical modelling, control design, simulation studies and fascinating experimental demonstrator prototypes. Closing the monograph is a chapter on the future research and technological challenges for snake robot locomotion (Chap. 14).

The series Editors have no doubt that the control and robotics community will find much of interest in this monograph. The monograph's progress through the historical record for the field, the proofs and descriptions of fundamental snake robot principles and the practical demonstrations using robot prototypes will ensure this new entry to the *Advances in Industrial Control* series becomes a key reference and source text for snake-robot locomotion research and development.

Industrial Control Centre
Glasgow
Scotland, UK

M.J. Grimble
M.A. Johnson

Preface

The purpose of this book is to present theoretical and practical topics related to snake robots. Snake robots are robotic mechanisms designed to move like biological snakes. The advantage of such mechanisms is their ability to move and operate in challenging environments where human presence is unwanted or impossible. Future applications of these mechanisms include search and rescue operations, inspection and maintenance in industrial process plants, and subsea operations. Research on snake robots has been conducted for several decades. For instance, the world's first snake robot was developed in Japan already in 1972. There are, however, still many theoretical and practical aspects of snake robot locomotion which have not yet been addressed in the snake robot literature. Current literature is characterised by numerous different approaches to modelling, development, and control of these mechanisms, but a unified theoretical foundation of snake robots has not yet been established.

In this book, we attempt to target these limitations of current literature on snake robots. The main goal of the book is to contribute to the mathematical foundation of the control theory of snake robots, and also stimulate and support future research on these fascinating mechanisms. To this end, the book is a complete treatment of snake robotics, with topics ranging from mathematical modelling techniques, mechatronic design and implementation, and control design strategies. In particular, several new approaches to modelling snake robot locomotion are presented. Moreover, numerous properties of snake robot dynamics are derived using nonlinear system analysis tools, and several new control strategies for snake robots are proposed. The book also describes the development of two snake robots that are employed to experimentally validate many of the theoretical results. Whereas previous literature has mainly focused on flat surface locomotion, a distinct feature of the book is the strong focus on locomotion in uneven and cluttered environments. The organisation of the book is detailed in Sect. 1.5.

Although the results presented in this book are new and based on recent conference and journal publications, they are presented at an initial level which is accessible to audiences with a standard undergraduate background in control theory or mechatronics. The book is written in a clear and easily understandable manner with numerous figures and pictures which help illustrate and visualise the material. The target audience of this book includes academic researchers and graduate students with an interest in snake robots or underactuated systems in general. The book may

also be used for self-study or as a reference by engineers and applied mathematicians, and by anyone who would like to find out more about the exciting field of snake robotics. We believe the book will be particularly useful to new researchers taking on a topic related to snake robotics since the book provides an extensive overview of the snake robot literature and also represents a suitable starting point for research in this area.

We are indebted to a number of people who have been integral to the completion of this book. We express our sincere gratitude to Professor Scott David Kelly (University of North Carolina at Charlotte), Professor Shugen Ma (Ritsumeikan University), and Professor Ole Morten Aamo (Department of Engineering Cybernetics at NTNU) for their feedback to the material in this book in conjunction with their participation in the doctoral dissertation of Pål Liljebäck.

Furthermore, we gratefully acknowledge all the support we have received from our friends and colleagues at the Department of Engineering Cybernetics at NTNU. In particular, we thank Idar Haugstuen for our cooperation in conjunction with his M.Sc. project on snake robots in 2009/2010. Moreover, we thank Christian Holden for providing useful feedback to the material in this book, and we thank Alexey Pavlov for our talks and his many useful suggestions regarding our research. For their untiring help and efforts with the experimental systems considered in this book, we thank Terje Haugen, Per Inge Snildal, and Glenn Angel at the mechanical workshop of the department. We also thank Stefano Bertelli for his positive spirit and for his help with documenting the experimental results.

We owe many thanks to our friends and colleagues at SINTEF Applied Cybernetics for their support and for contributing to a positive and stimulating work environment. In particular, we thank the Research Director, Sture Holmstrøm, for his enthusiasm and his willingness to financially support research on snake robots. We are thankful to Aksel A. Transeth, Sigurd Fjerdings, and Erik Kyrkjebø for their positivity and for our many interesting discussions related to snake robots over the last years. A special recognition goes to Aksel A. Transeth for contributing to the research underlying this book with his knowledge and expertise of snake robots. We thank Geir Mathisen, Espen Helle, and Knut Vidar Skjersli for their work on circuit boards and software for the experimental systems considered in the book. We are grateful to Anders Beitnes for conceiving the idea of a self-propelled fire hose, which initiated research on snake robots at SINTEF and NTNU. We also thank Wheeko and Kulko for their outstanding and obedient performance during experiments, and for never complaining about late work hours.

Finally, we express our deepest gratitude to the Norwegian University of Science and Technology (NTNU) and SINTEF for providing the resources and environment that made it possible to write this book, and to the Research Council of Norway for supporting our research on snake robots.

Trondheim, Norway

Pål Liljebäck
Kristin Y. Pettersen
Øyvind Stavdahl
Jan Tommy Gravdahl

Contents

1	Introduction	1
1.1	Background and Motivation	1
1.2	Biological Snakes	5
1.2.1	The Anatomy of Snakes	5
1.2.2	The Locomotion of Snakes	7
1.3	Previous Work on Modelling, Mechatronics, and Control of Snake Robots	10
1.3.1	Previous Work on Modelling and Analysis of Snake Robots	10
1.3.2	Previous Work on Implementation of Physical Snake Robots	16
1.3.3	Previous Work on Control of Snake Robots	22
1.4	The Scope of This Book	27
1.4.1	An Analytical Approach	27
1.4.2	Snake Robots Without a Fixed Base	27
1.4.3	A Planar Perspective	27
1.4.4	Locomotion Without Sideslip Constraints	28
1.4.5	Motion Based on Lateral Undulation	28
1.5	An Outline of This Book	28
1.5.1	Outline of Part I—Snake Robot Locomotion on Flat Surfaces	29
1.5.2	Outline of Part II—Snake Robot Locomotion in Cluttered Environments	32
1.6	Publications Underlying This Book	34

Part I Snake Robot Locomotion on Flat Surfaces

2	A Complex Model of Snake Robot Locomotion on Planar Surfaces	39
2.1	The Relation Between This Chapter and Previous Literature	40
2.2	Basic Notation	40
2.3	The Parameters of the Snake Robot	40
2.4	The Kinematics of the Snake Robot	42

2.5	The Ground Friction Models	45
2.5.1	The Friction Models and Their Role in This Book	45
2.5.2	A Coulomb Friction Model	46
2.5.3	A Viscous Friction Model	47
2.6	The Dynamics of the Snake Robot	48
2.7	Separating Actuated and Unactuated Dynamics	50
2.8	Partial Feedback Linearisation of the Model	52
2.9	Chapter Summary	54
3	Development of a Mechanical Snake Robot for Motion Across Planar Surfaces	55
3.1	The Relation Between This Chapter and Previous Literature	55
3.2	The Joint Actuation Mechanism	56
3.3	The Passive Wheels	58
3.4	The Power and Control System	59
3.5	The Experimental Setup of the Snake Robot	59
3.6	Chapter Summary	61
4	Analysis and Synthesis of Snake Robot Locomotion	63
4.1	The Relation Between This Chapter and Previous Literature	64
4.2	Introduction to Nonlinear Controllability Analysis	65
4.3	Stabilisability Properties of Planar Snake Robots	67
4.4	Controllability Analysis of Planar Snake Robots	68
4.4.1	Controllability with Isotropic Viscous Friction	69
4.4.2	Controllability with Anisotropic Viscous Friction	69
4.5	Analysis of Propulsive Forces During Snake Locomotion	74
4.6	Synthesis of Propulsive Motion for the Snake Robot	76
4.7	The Gait Pattern Lateral Undulation	80
4.8	The Control System of the Joints	81
4.8.1	A Simple Joint Controller	81
4.8.2	An Exponentially Stable Joint Controller	82
4.9	Analysis of Turning Motion During Lateral Undulation	82
4.10	Analysis of Relative Motion Between Consecutive Links During Lateral Undulation	85
4.11	Chapter Summary	86
5	Path Following Control and Analysis of Snake Robots Based on the Poincaré Map	89
5.1	The Relation Between This Chapter and Previous Literature	90
5.2	Introduction to Poincaré Maps	91
5.2.1	General Description of Poincaré Maps	91
5.2.2	Practical Application of Poincaré Maps	93
5.3	Straight Line Path Following Control of Snake Robots	94
5.3.1	Control Objective	94
5.3.2	The Straight Line Path Following Controller	95
5.4	Stability Analysis of the Path Following Controller Based on the Poincaré Map	96

5.4.1	Converting the Snake Robot Model to a Time-Periodic Autonomous System	97
5.4.2	Specification of the Poincaré Section for the Snake Robot	97
5.4.3	Stability Analysis of the Poincaré Map	98
5.5	Simulation Study: The Performance of the Path Following Controller	100
5.6	Chapter Summary	101
6	A Simplified Model of Snake Robot Locomotion on Planar Surfaces	103
6.1	The Relation Between This Chapter and Previous Literature	104
6.2	Overview of the Modelling Approach	104
6.3	The Kinematics of the Snake Robot	107
6.4	The Ground Friction Model	109
6.5	The Dynamics of the Snake Robot	112
6.5.1	The Translational Dynamics of the Snake Robot	112
6.5.2	The Rotational Dynamics of the Snake Robot	114
6.6	The Complete Simplified Model of the Snake Robot	115
6.7	Discussion of the Simplified Model	116
6.7.1	Applications of the Simplified Model	116
6.7.2	Accuracy Issues of the Simplified Kinematics	116
6.7.3	Accuracy Issues of the Ground Friction Model	117
6.7.4	Accuracy Issues of the Rotational Dynamics	118
6.8	Stabilisability Analysis of the Simplified Model	118
6.9	Controllability Analysis of the Simplified Model	119
6.10	Simulation Study: Comparison Between the Complex and the Simplified Model	122
6.10.1	Simulation Parameters	122
6.10.2	Relationship Between the Joint Coordinates in the Complex and Simplified Models	123
6.10.3	Comparison of Straight Motion	123
6.10.4	Comparison of Turning Motion	126
6.11	Chapter Summary	128
7	Analysis of Snake Robot Locomotion Based on Averaging Theory	131
7.1	The Relation Between This Chapter and Previous Literature	132
7.2	Introduction to Averaging Theory	132
7.3	The Velocity Dynamics During Lateral Undulation	133
7.4	The Averaged Velocity Dynamics During Lateral Undulation	135
7.5	The Steady-State Behaviour of the Velocity Dynamics During Lateral Undulation	136
7.6	Relationships Between the Gait Parameters and the Forward Velocity During Lateral Undulation	138
7.7	Simulation Study: Comparison Between the Original and the Averaged Velocity Dynamics	139
7.7.1	Simulation Parameters	139
7.7.2	Simulation Results	140

7.8	Simulation Study: Investigation of the Relationships Between Gait Parameters and Forward Velocity	142
7.8.1	Simulation Parameters	142
7.8.2	Simulation Results	143
7.9	Experimental Study: Investigation of the Relationships Between Gait Parameters and Forward Velocity	146
7.9.1	Layout of the Experiment	147
7.9.2	Experimental Results	149
7.10	Chapter Summary	151
8	Path Following Control of Snake Robots Through a Cascaded Approach	153
8.1	The Relation Between This Chapter and Previous Literature	154
8.2	Mathematical Preliminaries	154
8.3	Straight Line Path Following Control of Snake Robots	157
8.3.1	Control Objective	157
8.3.2	Assumptions	158
8.3.3	Model Transformation	158
8.3.4	The Straight Line Path Following Controller	160
8.3.5	The Stability Properties of the Path Following Controller	163
8.3.6	Proof of Theorem 8.2	164
8.4	Path Following Control of Snake Robots Along Curved Paths	167
8.4.1	Comments on the Curved Path Following Controller	167
8.4.2	The Curved Path Following Controller	168
8.5	Waypoint Guidance Control of Snake Robots	169
8.5.1	Description of the Approach	169
8.5.2	The Waypoint Guidance Strategy	170
8.6	Simulation Study: The Performance of the Straight Line Path Following Controller	171
8.6.1	Simulation Parameters	171
8.6.2	Simulation Results	172
8.7	Experimental Study: The Performance of the Straight Line Path Following Controller	172
8.7.1	Implementation Issues	173
8.7.2	Implementation of the Path Following Controller of the Physical Snake Robot	174
8.7.3	Experimental Results	175
8.8	Simulation Study: The Performance of the Waypoint Guidance Strategy	181
8.8.1	Implementation of the Guidance Strategy with the Simplified Model	182
8.8.2	Implementation of the Guidance Strategy with the Complex Model	182
8.8.3	Simulation Results	183
8.9	Chapter Summary	184

Part II Snake Robot Locomotion in Cluttered Environments

9	Introduction to Part II	189
10	A Hybrid Model of Snake Robot Locomotion in Cluttered Environments	193
10.1	The Relation Between This Chapter and Previous Literature	194
10.2	Hybrid Dynamical Systems and Complementarity Systems	195
10.2.1	Modelling of Hybrid Dynamical Systems	195
10.2.2	Complementarity Systems	196
10.3	The Dynamics of the Snake Robot Without Obstacles	197
10.3.1	The Ground Friction Model	198
10.3.2	The Equations of Motion Without Obstacles	199
10.4	Overview of the Contact Modelling Approach	200
10.5	Detection of Obstacle Impacts and Detachments	203
10.6	The Continuous Dynamics of the Snake Robot During Constrained Motion	204
10.6.1	The Unilateral Constraints from the Obstacles	205
10.6.2	The Constrained Dynamics of the Snake Robot Without Obstacle Friction	206
10.6.3	The Constrained Dynamics of the Snake Robot with Obstacle Friction	209
10.7	The Discontinuous Dynamics of the Snake Robot During Obstacle Impacts and Detachments	211
10.7.1	The Discontinuous Dynamics of the Snake Robot During Obstacle Impacts	211
10.7.2	The Discontinuous Dynamics of the Snake Robot During Obstacle Detachments	212
10.8	The Complete Hybrid Model of the Snake Robot in an Obstacle Environment	213
10.8.1	The Jump Set	213
10.8.2	The Jump Map	214
10.8.3	The Flow Set	214
10.8.4	The Flow Map	215
10.8.5	Summary of the Complete Hybrid Plant	215
10.9	Simulation Study: Comparison of the Hybrid Model with Previous Experimental and Simulation Results	215
10.10	Chapter Summary	216
11	Development of a Mechanical Snake Robot for Obstacle-Aided Locomotion	221
11.1	The Relation Between This Chapter and Previous Literature	221
11.2	Overview of the Snake Robot Design	222
11.3	The Exterior Gliding Surface	223
11.4	The Contact Force Measurement System	224
11.4.1	Assumptions Underlying the Sensor System	224

11.4.2	The Sensor System Setup	225
11.4.3	Calculation of Contact Forces	227
11.5	The Power and Control System	228
11.5.1	The Power System	228
11.5.2	The Control System	230
11.6	The Performance of the Snake Robot	231
11.6.1	Experimental Validation of the Contact Force Measurement System	231
11.6.2	Demonstration of Motion Patterns	232
11.7	The Experimental Setup of the Snake Robot	233
11.8	An Alternative Approach for Measuring External Contact Forces	235
11.9	Chapter Summary	237
12	Hybrid Control of Obstacle-Aided Locomotion	239
12.1	The Relation Between This Chapter and Previous Literature	240
12.2	Preliminary Note on Hybrid Controllers	241
12.3	Control Objective	242
12.4	Notation and Basic Assumptions	242
12.5	The Hybrid Controller for Obstacle-Aided Locomotion	244
12.5.1	The Leader-Follower Scheme	244
12.5.2	The Jam Detection Scheme	246
12.5.3	The Jam Resolution Scheme	246
12.5.4	The Joint Angle Controller	248
12.5.5	The Complete Hybrid Controller	248
12.6	Summary of the Closed-Loop System	251
12.7	Simulation Study: The Performance of the Hybrid Controller	252
12.7.1	Simulation Parameters	252
12.7.2	Attempting Lateral Undulation in Open-Loop in a Structured Obstacle Environment	253
12.7.3	Hybrid Controller in an Obstacle Environment	253
12.8	Experimental Study: The Performance of the Hybrid Controller	255
12.8.1	Experimental Setup	256
12.8.2	Experimental Results	256
12.9	Chapter Summary	263
13	Path Following Control of Snake Robots in Cluttered Environments	265
13.1	The Relation Between This Chapter and Previous Literature	266
13.2	A Controller Framework for Snake Robot Locomotion	266
13.3	Straight Line Path Following Control in Cluttered Environments	268
13.3.1	Control Objective	268
13.3.2	Notation and Basic Assumptions	269
13.3.3	The Body Wave Component	271
13.3.4	The Environment Adaptation Component	272
13.3.5	The Heading Control Component	273
13.3.6	The Joint Angle Controller	274
13.3.7	Summary of the Path Following Controller	274

- 13.4 Waypoint Guidance Control in Cluttered Environments 275
- 13.5 Simulation Study: The Performance of the Path Following
Controller 276
 - 13.5.1 Simulation Parameters 276
 - 13.5.2 Simulation Results 277
- 13.6 Experimental Study: The Performance of the Environment
Adaptation Strategy 279
 - 13.6.1 Experimental Setup 280
 - 13.6.2 Experimental Results 280
- 13.7 Chapter Summary 285
- 14 Future Research Challenges of Snake Robot Locomotion 287**
 - 14.1 Control Design Challenges 287
 - 14.2 Hardware Design Challenges 289
- Appendix A Proof of Lemma 8.2 293**
- Appendix B Proof of Lemma 8.3 295**
- Appendix C Low-Pass Filtering Reference Models 297**
 - C.1 A 2nd-Order Low-Pass Filtering Reference Model 297
 - C.2 A 3rd-Order Low-Pass Filtering Reference Model 298
- Glossary 301**
- References 303**
- Index 313**