Springer Tracts in Advanced Robotics 108

Editors

Prof. Bruno Siciliano
Dipartimento di Ingegneria Elettrica
e Tecnologie dell'Informazione
Università degli Studi di Napoli
Federico II
Via Claudio 21, 80125 Napoli
Italy
E-mail: siciliano@unina.it

Prof. Oussama Khatib
Artificial Intelligence Laboratory
Department of Computer Science
Stanford University
Stanford, CA 94305-9010
USA
E-mail: khatib@cs.stanford.edu

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Shane (S.Q.) Xie

Advanced Robotics for Medical Rehabilitation

Current State of the Art and Recent Advances

Springer

Shane (S.Q.) Xie
The Department of Mechanical Engineering
The University of Auckland
Auckland
New Zealand

ISSN 1610-7438 ISSN 1610-742X (electronic)
Springer Tracts in Advanced Robotics
ISBN 978-3-319-19895-8 ISBN 978-3-319-19896-5 (eBook)
DOI 10.1007/978-3-319-19896-5

Library of Congress Control Number: 2015950907

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Series Foreword

Robotics is undergoing a major transformation in scope and dimension. From a largely dominant industrial focus, robotics is rapidly expanding into human environments and vigorously engaged in its new challenges. Interacting with, assisting, serving and exploring with humans, the emerging robots will increasingly touch people and their lives.

Beyond its impact on physical robots, the body of knowledge robotics has produced is revealing a much wider range of applications reaching across diverse research areas and scientific disciplines, such as biomechanics, haptics, neurosciences, virtual simulation, animation, surgery and sensor networks, among others. In return, the challenges of the new emerging areas are proving an abundant source of stimulation and insights for the field of robotics. It is indeed at the intersection of disciplines that the most striking advances happen.

The *Springer Tracts in Advanced Robotics* (STAR) is devoted to bringing to the research community the latest advances in the robotic field on the basis of their significance and quality. Through a wide and timely dissemination of critical research developments in robotics, our objective with this series is to promote more exchanges and collaborations among the researchers in the community and contribute to further advancements in this rapidly growing field.

The monograph by Shane Xie presents the outcome of recent research results in the field of rehabilitation robotics, which is broadly surveyed. A number of novel methods are introduced including a physiological model of the masticatory system, a model of the human shoulder and elbow, a motion and interactive control of an exoskeleton for upper limb rehabilitation, a kinematic and computational model of human ankle, and an adaptive control of an ankle rehabilitation robot. Trends and opportunities for future advances in the design, modelling, control and development of medical robotic systems for rehabilitation are also discussed.

Most methods have been effectively implemented in experimental tests, and the source code of the robotic simulation and control is valuably provided. A fine addition to STAR!

Naples, Italy
September 2015

Bruno Siciliano
STAR Editor

Preface

Robots were used for rehabilitation purposes since the 1960s. Application of robots in rehabilitation was initially more focused on replacing lost functions in individuals with physical disabilities through the use of devices such as robotic orthoses, workstations, feeding devices and robotic wheelchairs. Over the last two decades, there has been an increasing amount of research into the use of robots in physical therapy. The goal of rehabilitation is to recuperate a patient from impairment or disability and improve mobility, functional ability and quality of life. This impairment can be the result of a stroke, a injury or a neurological disease.

Since robots are well suited for repetitive tasks and can be designed to have adequate force capabilities, their use in the execution of these exercises will be able to reduce the physical workload of therapists and can potentially allow the therapists to simultaneously oversee the treatment of multiple patients in a supervisory role. By using robotic devices, diagnosis and prognosis can be made more objectively with the help of quantitative data, and comparisons between different cases can also be made more easily. Several successful rehabilitation robots have undergone clinical trials and are currently being used in hospitals and clinics for neuromotor rehabilitation. However, the research and development of advanced robotics for medical rehabilitation are still at an early stage, and further research and development in this area are becoming more and more urgent.

This book systematically reviews the recent research and development of the innovative technologies for advanced robotics in medical rehabilitation. Through systematic overview of the existing systems and recent approaches of rehabilitation robots, interaction control and rehabilitation, the problems that emerged from recent approaches have been identified. To overcome these problems and to develop a series of novel advanced rehabilitation robotics, research and development of medical robotics for human impaired limbs have been carried out. These include the introduction of physiological masticatory model development, the modelling of human shoulder and elbow mechanisms, an exoskeleton development for upper limb rehabilitation, kinematic and computational model of human ankle, development of ankle rehabilitation robot and its adaptive control strategies. These research topics and findings constitute the main contents of this book.

The aim of this book is to provide a snapshot of our recent research outcomes and implementation studies in the field of advanced rehabilitation robotics. As the title suggests, Chap. 1 gives an overview of medical rehabilitation robotics. It briefly introduces the history and background of the medical robotics and this is followed by the discussion on the current issues involved in existing robotics and the motivation of our work presented in this book.

Chapter 2 presents the historical background of advanced robotics for medical rehabilitation. This chapter has highlighted the main motivations and objectives of this book through an overview of rehabilitation robots, interaction control and rehabilitation. The different types of rehabilitation devices developed in literatures were considered, with particular focus on their mechanical design, actuation methods and control schemes. Subsequently, studies relating to human limb kinematics and computational modelling of the ankle were also examined.

Targeting masticatory system modelling, Chap. 3 introduces the associated numerous complexities, and a new physiological model with two DOFs was developed for it. An in-depth study was performed on the mandibular muscles to properly characterise all accessible mandibular muscle EMG signals from which to base the physiological model. Based on the findings of the EMG signal study, the physiological model of the masticatory system was reconfigured and the concept of a hybrid model was introduced. The effectiveness of hybrid model was proven through experiments from multiple subjects and was analysed offline.

To further address the robotic system for upper limb, Chap. 4 proposes a kinematically redundant 4R spherical wrist model for shoulder and elbow joints, with its kinematics modelled by DH notation to solve the forward and inverse kinematic problems. This chapter also presents an EMG-driven physiological model of the elbow joint that was developed in the sagittal plane. In this chapter, the physiological model of the developed elbow joint model was coupled with linear envelope processing and experimentally validated with data from multiple subjects.

The design of an active upper limb exoskeleton prototype is presented in Chap. 5. A redundant 4R spherical wrist mechanism is proposed for a shoulder exoskeleton to solve the singularity and workspace limitations. The 4R mechanism has been optimised using multi-objective optimisation algorithm to achieve the entire human shoulder workspace while operating far away from singular configurations and without interfering with the user. Numerous important design factors were considered in this chapter in realising the final exoskeleton design to ensure that it can operate effectively alongside a human user's upper limb.

Chapter 6 further develops the motion and interactive control methods for upper limb exoskeleton. This chapter presents the minimum jerk trajectory planner, which is developed to generate smooth trajectories for the 5-DOF upper limb exoskeleton. This chapter also presents force-based control strategies that allow the exoskeleton to interact with and respond to the unpredictable behaviour of the user's limb. The concept of admittance and impedance in the interaction between two physical systems is discussed and applied to the exoskeleton system.

To model the human ankle joint, motion of the ankle–foot structure is discussed in Chap. 7. This chapter presents a computational ankle model developed to facilitate controller development of the ankle rehabilitation robot and provides a description of the ankle mechanical characteristics through considerations of forces applied along anatomical elements around the ankle joint, which include ligaments and muscle–tendon units. The dynamics of the ankle–foot structure and its surrounding ligaments and muscle–tendon units were formulated into a state space model to facilitate simulation of the robot. Finally, based on observations from preliminary testing, a modified recursive least squares algorithm was proposed and tested on experimental data.

Chapter 8 begins with an overview of the design requirements of an ankle rehabilitation robot. A suitable kinematic structure of the robot is then designed. Workspace, singularity and force analyses of mechanisms having this structure are then presented. This is followed by a description of the robot hardware and interface. Operation of the developed rehabilitation robot relies on implementation of a suitable interaction controller, and a force-based impedance control approach had been taken in this research. This chapter details the development of the multi-input multi-output (MIMO) actuator force controller devised in this work.

Chapter 9 further details the dynamic model of the parallel mechanism for ankle rehabilitation and presents variable impedance control approaches to achieve adaptive interaction control. In this chapter, the basic impedance control law is extended to yield a more advanced interaction control scheme for passive range of motion and active-assistive exercises. This chapter also explores the use of an assistance adaptation scheme to achieve the implementation of a control module to facilitate active user participation in the rehabilitation exercises.

Chapter 10 seeks to summarise the main outcomes and conclusions of this research, as well as highlight the contributions made in this book. This chapter also provides a discussion of future directions that can be explored to extend or advance the work presented in this book. The future trends in various aspects including the design, modelling and control of the advanced robotics for medical rehabilitation are discussed. This may be used to guide coming research, or act as a reference for institutions to design and develop new medical robotic systems.

This book also contains an Appendix that summarises some of the design and development of rehabilitation robotics. It provides the source code of the robotic simulation and control. These are excellent examples for users or developers.

I would like to take this opportunity to express my deep appreciation to those who have contributed to this book. The authors are also grateful to Wei Meng, Yun Ho Tsoi, James Pau and Ho Shing Lo for their assistance in compiling the book. It is our sincere hope that readers will find this book useful to their study and research.

Auckland, New Zealand Shane (S.Q.) Xie
March 2015

Acknowledgments

The authors would like to acknowledge funding support from the Foundation for Research, Science and Technology of New Zealand, the Auckland Medical Research Foundation, the Lottery Healthcare Research Foundation and the University of Auckland.

Contents

Nomenclature

3D	Three-dimensional
Abduction	Drawing a limb away from the median sagittal plane (e.g. raising the shoulder)
Abduction/external rotation	Rotation of the foot on the transverse plane so that the big toe is moved away from the sagittal plane of the human body
AC	Activity coefficient
Adduction	Bringing a limb closer to the median sagittal plane (e.g. lowering the shoulder)
Adduction/internal rotation	Rotation of the foot on the transverse plane so that the big toe is moved closer towards the sagittal plane of the human body
Ankle/talocrural joint	The articulation between the tibia, fibula and talus
ANN	Artificial neural network
Anterior	In anatomy, nearer the forward end, or front of a human
AR	Autoregressive (coefficients)
Bilateral	Of both sides
CC	Correlation coefficient
CE	Contractile element
CMOS	Complementary metal–oxide–semiconductor
CMRR	Common-mode rejection ratio—ability of a device to reject common input signals (noise)
Concentric contraction	Condition where skeletal muscle shortens during a contraction (and overcomes external resistance)
Condition number	The ratio of the maximum to minimum singular values of a matrix
Contralateral	On the opposite side of the body
CPM	Continuous passive motion
DE	Differential evolution
DOF	Degree of freedom

Dorsiflexion	Rotation of the foot on the sagittal plane so that the toes are brought closer towards the shank
DSP	Digital signal processing
Eccentric contraction	Condition where skeletal muscle lengthens during a contraction (usually an already shortened muscle acting in a braking capacity)
EDF	Error dependency function
EEG	Electroencephalography—non-invasive measure of electrical brain activity taken from the surface of the scalp
EKF	Extended Kalman filter
Electromechanical delay	The time delay between the initiation of a muscle contraction and actual movement
EMA	Electromagnetic articulograph—device to track mandibular movement
EMG	Electromyography—non-invasive measure of electrical muscle activity taken from the skin surface
Euler angles	A sequence of angles used to define orientation of an object through consecutive rotations about the specified axes. For example, XYZ Euler angles give the X rotation about the x-axis, followed by a Y rotation about the resulting y-axis and then the Z rotation about the resulting z-axis
Eversion	Rotation of the foot so that the medial side of the foot is moved away from the sagittal plane of the human body
Exoskeleton	Powered anthropomorphic robotic device that moves in concert with a user
FFT	Fast Fourier transform
Frontal plane	The anatomical plane separating the body into front and back portions
GA	Genetic algorithm
GUI	Graphical user interface
HPF	High-pass filter
IMU	Inertial measurement unit
In vivo	Within a living environment
Inversion	Rotation of the foot so that the lateral side of the foot is moved closer to the sagittal plane of the human body
Ipsilateral	On the same side of the body
Isometric contraction	Muscle contraction during which muscle length is constant (only force increases)
Joint space	Generalised coordinates used to describe the motion or force quantities along the actuators of a robot
Lateral	Used to describe the side of a body part which is away from the sagittal plane of the human body

LE	Linear envelope—the result of linear envelope processing (LEP)
LEP	Linear envelope processing—filtering process that produces a smoothed signal, which is called a linear envelope
LMS	Least mean square
LPF	Low-pass filter
Manipulator Jacobian	A matrix describing the linear mapping between the joint space velocity and task space velocity
MAV	Mean absolute value—a time-domain feature of the EMG signal
MC	Movement coefficient
Medial	In anatomy, pertaining to the inside and closer to the midline
Medial	Used to describe the side of a body part which is facing towards the sagittal plane of the human body
MEM	Matrix element matching
MIMO	Multi-input multi-output
MMG	Mechanomyography—non-invasive measure of the surface oscillations of the skin during muscle contraction
MSE	Mean square error
MU	Motor unit—a motor neuron and all the muscle fibres it innervates
MUAP	Motor unit action potential—electrical impulse that stimulates contraction of a motor unit's muscle fibres
MVC	Maximum voluntary contraction—maximum contraction attainable without causing pain or discomfort
Myoelectric signal	Another name for the EMG signal
NI	Neuromuscular interface—all the hardware and software components involved in converting the raw EMG signals of a joint into an equivalent torque or displacement
Null space	A column-wise collection of the null vectors of a matrix
Null vector	A null vector of a matrix is a column vector of unit length whereby the matrix multiplication of this matrix and the null vector will result in a zero vector
PCB	Printed circuit board
PE	Parallel-elastic element
Plantarflexion	Rotation of the foot on the sagittal plane so that the toes are brought away from the shank
Posterior	In anatomy, nearer the back end, i.e. back of a human

Pronation	Rotational movement of the forearm that causes the palm to face downwards
Rank deficient	A matrix is considered to be rank deficient if it has zero as a singular value
RLS	Recursive least square
RMS	Root mean square—a time domain feature of the EMG signal
RMSE	Root mean square error—measure of average error between two sets of data collected over a set period of time
Robot singularity	A point in the robot workspace whereby the manipulator Jacobian becomes rank deficient
ROM	Range of motion
Sagittal plane	In anatomy, the vertical plane that passes from the front to rear of the body, dividing it into left and right halves
Sagittal plane	The anatomical plane separating the body into left and right portions
SDOF	Single degree of freedom
SE	Series elastic element
Shank	The portion of the lower limb between the knee and the ankle
Singular values	The values along the leading diagonal of the rectangular diagonal matrix resulting from the singular value decomposition of a matrix
Singular value decomposition (SVD)	A matrix factorisation that represents a rectangular matrix as the product of a unitary matrix, a rectangular diagonal matrix with non-negative real numbers along its diagonal and another unitary matrix
SISO	Single-input single-output
Subtalar joint	The articulation between the talus and calcaneus
Supination	Rotational movement of the forearm that causes that palm to face upwards
Task space	Generalised coordinates used to describe the motion or force quantities in the operational space of a robot
TMJ	Temporomandibular joint—connects the mandible to the maxilla at the base of the skull
TMJD	Temporomandibular joint disorder
Transverse plane	The anatomical plane separating the body into top and bottom portions