

David Baiden

Interaction Control of a Robotic Rehabilitation Device using Inherent Compliant Actuators with Pneumatic Rotary Elastic Chambers

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David Baiden

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David Baiden

Abstract

In modern robotics humans and machines are closing rank in industry for manufacturing processes, in private homes for automated service delivery and in health care for the rehabilitative purpose of kinesitherapy. Since both participants share the workspace and possibly get in direct physical contact, new particular requirements emerge for the robotic system with regard to an appropriate interaction control as well as for a correspondingly aligned drive technology. In order to prevent injuries, compliant actuator designs in combination with low accelerated masses are well suitable, in which the compliance can either be realized actively by control or passively by the integration of elastic materials. This however implies the problem of a reduced position or force control performance and especially the need for an interaction controller, which is equally matched to the compliant actuators and the application purpose to establish an appropriate human-robot cooperation.

The present dissertation is dedicated to research and development of different interaction control concepts for an exoskeleton robot with inherent compliant actuation on the basis of fluidic direct drives with *Rotary Elastic Chambers* (REC). Moreover, it is investigated which kind of interaction or effect can be achieved, if the complexity of plant models and control structures is kept as low as possible.

Initially, the requisitions for controlling such systems are formulated and the characteristics of fundamental control concepts and actuator types are considered. The first part of the thesis is concerned about modeling of the pneumatic rotary actuators by using experimental as well as phenomenological approaches. In this regard, the actuator model is divided into pneumatic and mechanic subsystems and existing models are modified or extended and enhanced. To fulfill the particular demands and improve the controller accuracy, static torque characteristics are combined with different friction compensation models and a solution is implemented to independently adjust the output torque and joint rigidity.

The second part of this dissertation focuses on the development of interaction controllers that manage without force/torque sensors, which allows to save costs to a large extent. For this purpose, a planar 3 degrees of freedom (DoF) exoskeleton robot equipped with REC actuators is available, which can partly support the lower extremities of a person. As application example an activity of daily living from the area of rehabilitation is chosen, in which elderly people or slightly physically restricted stroke patients should perform repetitive sit-to-stand exercises.

The overall development goal is to provide a suitable combination of compliant actuator and supportive interaction controller to facilitate and successfully complete the sit-to-stand process in a way, that the user is not passively guided along a fixed predefined trajectory, but is mostly self-determined with own authority and only influenced by the robot as little as possible. The presented concepts in this context begin from a simple almost model-free master-slave approach with individual trajectory generation, to the usage of active virtual joint admittances with temporal reference trajectory, through the realization of variable passive joint rigidity. An adaptive iterative learning concept in the Cartesian space eventually allows temporal and spatial freedom of movement. The functionality of the pursued approaches is evaluated by means of practical experiments with healthy and partially physically impaired subjects. In conclusion, the achieved outcomes are described and possible application purposes are named.

Kurzfassung

In der modernen Robotik rücken Menschen und Maschinen sowohl in der Industrie bei Fertigungsprozessen, im privaten Heim zur automatisierten Erbringung von Dienstleistungen als auch im Gesundheitswesen zwecks bewegungstherapeutischer Rehabilitation immer näher zusammen. Da sich beide Beteiligten den Arbeitsbereich teilen und gegebenenfalls in direktem physischen Kontakt befinden, entstehen neue spezielle Ansprüche an das Robotersystem hinsichtlich einer geeigneten Interaktionsregelung sowie der Bedarf einer damit harmonisierenden Antriebstechnologie. Um Verletzungen vorzubeugen, eignen sich nachgiebige Antriebskonzepte in Verbindung mit geringen beschleunigten Massen, bei denen die Nachgiebigkeit entweder aktiv durch einen Regler oder passiv durch die Integration von elastischen Werkstoffen erzeugt werden kann. Damit einher geht allerdings die Problematik einer verringerten Positions- bzw. Kraftregelungsgüte und insbesondere der Bedarf einer gleichermaßen auf die nachgiebigen Antriebe und den Anwendungszweck abgestimmten Interaktionsregelung zur Kooperation mit dem Menschen.

Die vorliegende Dissertationsschrift widmet sich der Erforschung und Entwicklung von unterschiedlichen Interaktionsregelungskonzepten für einen Exoskelett-Roboter mit inhärent nachgiebigen Aktoren auf Basis von fluidischen Direktantrieben mit elastischen Rotationskammern (engl.: *Rotary Elastic Chambers* – REC). Zudem wird untersucht, welche Art der Interaktion bzw. Wirkung erreicht werden kann, wenn die Komplexität von Streckenmodellen und Reglerstrukturen möglichst gering gehalten wird.

Zunächst werden die Anforderungen an die Regelung solcher Systeme formuliert und die Eigenschaften von grundlegenden Reglerkonzepten sowie Antriebstypen betrachtet. Der erste Teil dieser Arbeit befasst sich mit der Modellierung der pneumatischen Rotationsantriebe unter Verwendung von experimentellen und phänomenologischen Ansätzen. Dabei wird das Antriebsmodell in Subsysteme für Pneumatik und Mechanik unterteilt und bestehende Modelle modifiziert bzw. erweitert. Um den besonderen Erfordernissen gerecht zu werden und die Regelgenauigkeit zu verbessern, werden statische Drehmomentcharakteristiken mit verschiedenen Reibungskompensationsmodellen kombiniert und eine Lösung zur unabhängigen Einstellung von Drehmoment und Antriebssteifigkeit realisiert.

Der zweite Teil dieser Dissertation behandelt die Entwicklung von Interaktionsreglern, die ohne die Verwendung von Kraft-/Momentensensoren auskommen, wodurch sich Kosten in hohem Umfang einsparen lassen. Zu diesem Zweck steht ein dreigelenkiges planares Exoskelett mit REC-Antrieben zur Verfügung, welches die unteren Extremitäten teilweise unterstützen kann. Als Anwendungsbeispiel wird aus dem Bereich Rehabilitation eine Aktivität des täglichen Lebens gewählt, bei der ältere Personen oder körperlich leicht eingeschränkte Schlaganfallpatienten durch repetitive Übungen den Transfer vom Sitz in den Stand durchführen sollen.

Das Gesamtentwicklungsziel besteht darin, mit einer Kombination aus nachgiebigem Aktor und Interaktionsregler den Aufstehprozess so zu unterstützen und erfolgreich abzuschließen, dass der Benutzer nicht passiv auf einer fest vorgegebenen Trajektorie geführt wird, sondern größtenteils selbst die Kontrolle behält und vom Roboter so wenig wie möglich beeinflusst wird. Die diesbezüglich vorgestellten Konzepte reichen von einem einfachen nahezu modell-freien Master-Slave Ansatz mit individueller Trajektoriengenerierung, über die Verwendung von aktiven virtuellen Gelenkadmittanzen mit zeitlicher Solltrajektorie bis hin zur Realisierung variabler passiver Gelenksteifigkeiten. Ein adaptives iterativ lernendes Konzept im kartesischen Raum erlaubt schließlich zeitliche und örtliche Bewegungsfreiheit. Die Funktionalität der verfolgten Ansätze wird anhand praktischer Experimente mit gesunden und teils körperlich beeinträchtigten Testpersonen evaluiert. Abschließend werden die erreichten Resultate beschrieben und mögliche Anwendungszwecke angeführt.

“There are no shortcuts to any place worth going.”
Beverly Sills

Contents

1	Introduction	1
1.1	Motivation	1
1.1.1	Application Domains	2
1.1.2	Aspects of Physical Human-Machine Interaction	3
1.1.3	Examples of Robotic Devices for Movement Training	4
1.1.4	Complex Interaction Between Human and Robot	7
1.2	Objectives and Contribution	9
1.3	Structure of the Thesis	11
2	Background about Human-Machine Interaction and Compliant Actuators	13
2.1	Importance of Compliant Actuation for Physical HRI	13
2.1.1	Aspects of Safe and Dependable Robots	13
2.1.2	Approaches to Realize Compliant Robot Behavior	15
2.2	Overview: Commonly Applied Methods for Interaction Control	16
2.2.1	Basic Control Concepts	17
2.2.2	Components of Torque and Interaction Control Strategies	18
2.2.3	Control Concepts of Physically Supportive Robots	25
2.3	Compliant Actuators and their Basic Characteristics	26
2.3.1	The Ideal Actuator	27
2.3.2	Actuators with Compliant Elements	27
2.3.3	The Pneumatic Soft-Actuators with Rotary Elastic Chambers	32
3	Background about REC Actuator Modeling and Control	37
3.1	General Modeling Strategies	37
3.2	Specific Properties of the REC Actuators	39
3.2.1	Torque Characteristic	39
3.2.2	Volume Characteristic	42
3.2.3	Stiffness Properties	43
3.2.4	Measurement of Static Actuator Torque Characteristics	44
3.3	Control of the REC Actuator Subsystem	46
3.3.1	Model-Based Pressure Control	47
3.3.2	Robust Position Control with Delta-Pressure Principle	51
3.3.3	Torque Control Based on Inverted Data Maps	57
4	Enhancements of Pneumatic Rotary Soft-Actuator Control	59
4.1	The Need for an Actuator Model as Appropriate Interface for HRI Control	59
4.1.1	Torque Map Accuracy	59
4.1.2	Effects of the Delta-Pressure Principle	61
4.1.3	Linear and Nonlinear Parameter Identification	67
4.2	Hysteresis Modeling of the Antagonistic Acting Actuator	71
4.2.1	Basic Hysteresis Characteristic of the Single Actuator Chamber	72
4.2.2	Hysteresis Characteristic of the Antagonistic Actuator	73
4.2.3	Friction Modeling	75
4.2.4	Extraction of Angle-Torque Hysteresis	78

4.2.5	Hysteresis Reproduction Based on Modified Maxwell-Slip Models . . .	82
4.2.6	Discussion	96
4.3	Independent Torque and Stiffness Adjustment	96
4.3.1	Analogy to Parallel Couplings of Springs	97
4.3.2	Determination of the Torque Characteristic	100
4.3.3	Parametric Torque Characteristics	102
4.3.4	REC Actuator Model with Independent Torque and Stiffness Interfaces	104
4.3.5	Simulation Analysis	105
4.3.6	Evaluation Results	107
4.3.7	Discussion	112
4.4	Enhanced REC Actuator Control	113
4.4.1	Hysteresis Compensation in the Interaction Controller Loop	113
4.4.2	Position Control with Friction Compensation	115
4.4.3	Stiffness Adjustment with Friction Compensation	116
4.4.4	Discussion	120
5	Human-Robot Interaction Control	121
5.1	Realization of Compliant Motion	121
5.2	The Applied Robot with Pneumatic Rotary Soft-Actuators	122
5.2.1	Hardware Description of the Lower Extremities Exoskeleton	122
5.2.2	Robot Support in Certain Movement Phases	123
5.3	Trajectory Generation for Time-Dependent Interaction Control Concepts	125
5.3.1	Averaged Biomechanical Data of Clinical Surveys	126
5.3.2	Movement Teach-In for Time-Based Trajectory Recording	126
5.3.3	Reference Trajectory Scaling	127
5.4	Master-Slave Position Control	127
5.4.1	Basic Effect of the Control Concept	129
5.4.2	Human Involvement and Support Generation	132
5.4.3	Results - First Experiments with Healthy Subjects	136
5.4.4	Discussion	138
5.5	Motion Control with Adjustable Active Admittance	138
5.5.1	Components of the Implemented Controller	139
5.5.2	Interaction Torque Estimation	145
5.5.3	Experimental Results	148
5.5.4	Discussion	153
5.6	Trajectory Generation for Time-Independent Interaction Control Concepts	154
5.6.1	Position Reference without Temporal Coupling	155
5.6.2	Movement Teach-In Based on the Neural Gas Approach	155
5.7	Time-Independent Motion Control with Adjustable Passive Actuator Stiffness	161
5.7.1	Posture Correction and Movement Support in Joint Space	161
5.7.2	Experimental Results	164
5.7.3	Discussion	167
5.8	Time-Independent Adaptive Force Field Controller	168
5.8.1	Position-Based Force Field Controller	168
5.8.2	Necessity of Support Adaption	182
5.8.3	Iterative Learning Approach	183
5.8.4	Experimental Results	188
5.8.5	Discussion	199

6 Conclusion and Future Directions	201
6.1 About Actuator Modeling and Control	201
6.2 About Human-Robot Interaction Control	203
6.3 Future Directions	207
A Kinematic Relationships	209
B Jacobian	213
C Dynamic Model of the Robot	217
D Graphical User Interface and Development Environment	223
E Tests with Hemiplegic Stroke Survivors	227
F Inherent Compliant Hybrid Actuators	231
List of Symbols	237
Bibliography	249