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Daniel Sebastian Leidner

Cognitive Reasoning for Compliant Robot Manipulation

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To my brother Björn

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 robotics 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 Daniel Sebastian Leidner is based on the author's doctoral thesis. It conjugates the two research worlds of artificial intelligence and robotics in one original work on cognitive reasoning for compliant robot manipulation. Representation, planning, execution, and interpretation of constrained manipulation tasks naturally lead to the concept of intelligent physical compliance. These methodological issues are keenly discussed along with supporting practical issues, clearly demonstrating the potential of cognition-enabled service robots.

Rich of examples developed by means of extensive experimentation on a humanoid robotic platform both on ground and in a space context, this volume was the winner of the 2018 Georges Giralt PhD Award for the best doctoral thesis in Europe. A very fine addition to the STAR series!

Naples, Italy
October 2018

Bruno Siciliano
STAR Editor

Preface

This manuscript is the result of six years of research conducted between 2011 and 2017 at the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR). The findings were elaborated in cooperation with the Institute for Artificial Intelligence at the University of Bremen. This exceptional alliance between two of the world's leading research facilities on artificial intelligence and robotics enabled me to realize this work.

Accordingly, I would first like to express my utmost gratitude to my supervisors, Prof. Michael Beetz and Prof. Alin Albu-Schäffer, for the opportunity to live out this relationship under their guidance. In addition, I would like to thank Christoph Borst for his trust in my qualities as a robotics researcher that allowed me to work in one of the most inspiring environments. My special thanks go to Florian Schmidt, who introduced me to the world of robotics and continually supported me during my research. Furthermore, I would like to thank Dr. Alexander Dietrich, which whom I collaborated in several publications leading to a better understanding of the interconnections between high-level reasoning and low-level control. Thanks to Georg Bartels, for the interesting and fruitful discussions during our research stays, which resulted in many valuable ideas. Thanks to my former students, Peter Birkenkampf and Wissam Bejjani, for their support.

My deep gratitude goes to the entire support team of Rollin' Justin for the maintenance of the robot, which are Thomas Gumpert, Werner Friedl, Martin Heumos, Robert Burger, Alexander Beyer, and Dr. Jörg Butterfass.

Special thanks go to the METERON SUPVIS Justin team, who helped to push the robot to the limits, resulting in an excellent experiment. In particular, I would like to thank Dr. Neal Y. Lii, Peter Birkenkampf, Ralph Bayer, and Benedikt Pleintinger.

Moreover, I would like to thank the people proofreading this book: Dr. Neal Y. Lii, Dr. Alexander Dietrich, Dr. Maxime Chalon, and Dr. Freek Stulp.

Thanks to my parents Birgit and Lothar, who supported me during my entire life, always believing in my strengths. Finally, I would like to thank my wife Hanna for her love. Without her patience and her support while raising our newborn son Leon Maximilian, I would have been unable to finish this work.

Munich, Germany Daniel Sebastian Leidner
May 2017

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List of Used Symbols and Abbreviations

The used symbols appear in equations or within the description of algorithms. Their meaning remains thereby consistent throughout the entire manuscript, if not otherwise stated. The listed pseudocode shall be considered independent of any concrete implementation, yet it is derived from Python syntax. Assignments of variables are thereby denoted by the left arrow symbol (e.g., $\gamma \leftarrow 0$). List attachments are denoted by the concatenation operator, where angle brackets encompass the element to be attached (e.g., $\boldsymbol{X}^\frown\langle \boldsymbol{x}_{\text{end}} \rangle$).

In the following, the most frequent quantities and abbreviations of prominent importance are listed. They may appear with different subscripts and superscripts, where a dot donates a total derivative with respect to time t. Scalar quantities are printed as plain letters (e.g., α, $l_{\max}$, $\mathcal{O}$). Vectors and matrices are bold (e.g., $\dot{\boldsymbol{x}}, \boldsymbol{f}_{\text{ext}}$, $\boldsymbol{P}$). The meaning of the symbols is not further specified at this point, but detailed in the respective chapters they are introduced.

Symbols

α	Action Template
γ	Tier value for a particular action
δ	Step size
μ	Mean value
σ	Standard deviation
i, j, k	Indices for numbering and iterations
n	Node element in a graph
r	Reachability index
t	Time
x, y	Particle coordinates
N, M	Numbers (e.g., number of robot joints)
$\mathcal{O}$	Object of interest
V	Spring potential

$\boldsymbol{\lambda}$	Discretized A* map
$\boldsymbol{\tau}$	Vector of joint torques
$\boldsymbol{\varphi}$	Region of interest
$\boldsymbol{e}$	List of effects
$\boldsymbol{f}$	Vector of (generalized) Cartesian forces
$\boldsymbol{p}$	List of preconditions
$\boldsymbol{q}$	Link-side joint configuration
$\boldsymbol{x}$	Vector of Cartesian coordinates
$\mathcal{A}$	List of Action Templates
$\boldsymbol{\Phi}$	List of low-level robot commands
$\boldsymbol{\Omega}$	List of elemental robot operations
$\mathcal{C}$	Controller parameter vector
$\mathbf{D}$	Positive definite damping matrix
$\mathcal{G}$	Geometric state of the environment
$\boldsymbol{J}$	Jacobian matrix
$\mathcal{P}$	Particle distribution state
$\mathcal{S}$	Symbolic state of the environment
$\mathcal{T}$	Transition vector (symbolic or geometric)
$\boldsymbol{Q}$	Configuration space trajectory
$\boldsymbol{X}$	Cartesian trajectory

Abbreviations

act	Actual
cmd	Command
des	Desired
dev	Deviation
e.g.	Exempli gratia (for example)
eef	End effector
ext	External
i.e.	Id est (that is)
max	Maximum
min	Minimum
w.r.t.	With respect to
AI	Artificial intelligence
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DOF	Degree(s) of freedom
ESA	European Space Agency
ISS	International Space Station
KDE	Kernel density estimation
METERON	Multi-purpose End-To-End Robotic Operation Network
MST	Minimum spanning tree

OpenRAVE	Open Robotics Automation Virtual Environment
PDDL	Planning Domain Definition Language
ROI	Region of interest
RRT	Rapidly Exploring Random Trees
SDG	Semantic directed graph
TCP	Tool center point
TSP	Traveling salesperson

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Abstract

Physically compliant contact is a major element for many tasks in everyday environments. A universal service robot that is utilized to collect leaves in a park, polish a workpiece, or clean solar panels requires the cognition and manipulation capabilities to facilitate such compliant interaction. Evolution equipped humans with advanced mental abilities to envision physical contact situations and their resulting outcome, dexterous motor skills to perform the actions accordingly, as well as a sense of quality to rate the outcome of the task. In order to achieve human-like performance, a robot must provide the necessary methods to represent, plan, execute, and interpret compliant manipulation tasks. This manuscript covers those four steps of reasoning in the concept of *intelligent physical compliance*.

The contributions advance the capabilities of service robots by combining artificial intelligence reasoning methods and control strategies for compliant manipulation. A classification of manipulation tasks is conducted to identify the central research questions of the addressed topic. Novel representations are derived to describe the properties of physical interaction. Special attention is given to wiping tasks which are predominant in everyday environments. It is investigated how symbolic task descriptions can be translated into meaningful robot commands. A particle distribution model is used to plan goal-oriented wiping actions and predict the quality according to the anticipated result. The planned tool motions are converted into the joint space of the humanoid robot Rollin' Justin to perform the tasks in the real world. In order to execute the motions in a physically compliant fashion, a hierarchical whole-body impedance controller is integrated into the framework. The controller is automatically parameterized with respect to the requirements of the particular task. Haptic feedback is utilized to infer contact and interpret the performance semantically. Finally, the robot is able to compensate for possible disturbances as it plans additional recovery motions while effectively

closing the cognitive control loop. Among others, the developed concept is applied in an actual space robotics mission, in which an astronaut aboard the International Space Station (ISS) commands Rollin' Justin to maintain a Martian solar panel farm in a mock-up environment. This application demonstrates the far-reaching impact of the proposed approach and the associated opportunities that emerge with the availability of cognition-enabled service robots.