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Bruno Siciliano · Fabio Ruggiero
Editors

Robot Dynamic Manipulation

Perception of Deformable Objects and Nonprehensile Manipulation Control

Springer

Editors
Bruno Siciliano
Department of Electrical Engineering
University of Naples Federico II
Naples, Italy

Fabio Ruggiero
Department of Electrical Engineering
University of Naples Federico II
Naples, Italy

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Foreword

At the dawn of the century's third decade, robotics is reaching an elevated level of maturity and continues to benefit from the advances and innovations in its enabling technologies. These all are contributing to an unprecedented effort to bringing robots to human environment in hospitals and homes, factories, and schools; in the field for robots fighting fires, making goods and products, picking fruits, and watering the farmland, saving time and lives. Robots today hold the promise for making a considerable impact in a wide range of real-world applications from industrial manufacturing to healthcare, transportation, and exploration of the deep space and sea. Tomorrow, robots will become pervasive and touch upon many aspects of modern life.

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.

Bruno Siciliano and Fabio Ruggiero present in this book the results and accomplishments in RoDyMan, a European Research Council's project on robotic dynamic manipulation. This project brought a strong team of robotics researchers with a wide range of complementary skills and competencies to work together on the challenges of nonprehensile dynamic manipulation and deformable object manipulation. The Pizza Maker, which was selected as the robot demonstrator, constitutes a compelling robotic benchmark in this project and marks a vivid signature of the project's host city, Naples.

The book is organized in two parts addressing the real-time perception and the planning and control of deformable objects and nonprehensile manipulation challenges. In its nine chapters, this collection offers a comprehensive treatment of dynamic manipulation and establishes significant advances in the theoretical formulation and experimental validation of nonprehensile robotic manipulation systems.

The outcome is a book which is confirmed to be shining in our STAR series!

Stanford, USA
September 2021

Oussama Khatib
STAR Editor

Preface

This book collects the main results of the Advanced Grant project RObotic DYnamic MANipulation (RoDyMan) funded by the European Research Council (ERC) to the first editor from June 2013 to May 2019.

The project started from observing that nonprehensile dynamic manipulation can be reasonably considered the most complex manipulation task. In a nonprehensile manipulation task, the object can still be manipulated by the hand. However, it is possible neither to prevent any infinitesimal motions of the object nor to resist all external wrenches applied to it. Think of an object held by the palm of a human hand: the object is sustained, and it is not dropped; however, it is not possible to resist to a force lifting the object, while it is possible to manipulate it by either moving the hand or breaking the contact by throwing. Both prehensile and nonprehensile manipulation become even more demanding if the handled object is not rigid. Several objects that humans handle every day are subject to both plastic and elastic deformations, such as newspapers, sheets, food, banknotes, tissues, bags, pillows, sponges. Understanding how to manage a deformable object and make it assume the desired shape is something very challenging. It might be argued that all such tasks are still rather far from being fully solved and applied in robotics, reducing the opportunities for broad adoption of robots within human co-habited environments.

As a final demonstrator of the RoDyMan project, we thought to realize a pizza-maker robot. This represents a perfect example to understand the robot challenge, considering the difficulties that every inexperienced person encounters in preparing a pizza having to manipulate a mixture of water and flour, of every varying shape and consistency.

Through RoDyMan, we got the opportunity to merge all the acquired competencies in a blended theoretical and technological challenge, advancing the state of the art in nonprehensile dynamic manipulation, also considering deformable objects. The RoDyMan project contributed to paving the way towards enhancing autonomy and operational capabilities of service robots.

The teamwork produced tangible results during the project. The developed platform often mentioned throughout this book is a humanoid-like robot with a pan-tilt sensorized robotic head, a two-degree-of-freedom (DoF) torso, two seven-DoF arms, and an omnidirectional mobile platform. The pizza-maker demonstrator was realized in all its aspects in simulation, and at 90% in the experimental phase.

From a theoretical point of view, several significant advances in the mathematical formulation of nonprehensile manipulation tasks were produced. Port-Hamiltonian, Lagrangian, and geometric control frameworks were chosen to handle nonprehensile manipulation problems. As concerns with perception, the main modules regarding environmental awareness were successfully developed. It was possible to model and track 3D deformable and texture-less objects subject to both elastic and plastic deformations. As said above, the possibility to take care also of possible fractures of the deformable object was considered. The viscosity of the pizza dough was taken into account by modeling a deformable object through a smoothed-particle hydrodynamic approach.

Unforeseen applications were found in the industrial scenario to glue the sole on the shoe upper. Also, the connection between nonprehensile manipulation and walking gaits of a legged robot is currently carried on in follow-up projects (WELDON, PRINBOT) after the successful experience of the RoDyMan project. Last but not the least, several of the developed control techniques can be applied within the robotic surgery field (MUSHA, PROSCAN, BARTOLO, PACMAN projects), and it is foreseeable to adopt similar methodologies for manipulation of soft tissues, muscles, organs, and the skin.

Regarding the engagement and outreach of the project, the scientific community, the media, and the general public warmly recognized the developed work. Several collaborations with international research groups were established. The RoDyMan project had a wide track record of dissemination to press and general public. The project was covered by media like Scientific American, The Times, The Telegraph, and Mashable. The RoDyMan robot was also exhibited at the Maker Faire European Edition 2017, in Rome, where it was awarded the Maker of Merit recognition.

As stated above, the main results achieved during the RoDyMan project have been collected in this book. Its contents are organized in two parts for a total of nine chapters by nine contributors: Part I deals with perception and includes four chapters on modeling, recognition, motion planning, and tracking of objects undergoing different types of deformation, e.g., elastic, plastic, fractures, collisions. The five chapters in Part II cover several aspects of nonprehensile manipulation planning and control for robotic systems, subject to both holonomic and nonholonomic constraints.

The contents have been duly updated and pedagogically organized in a harmonious way to highlight connections between the already published works. Besides, this book presents newly developed and unpublished results. In particular, Chaps. 3, 4, and 9 contain novelties in the face of the current literature. The notation has been homogenized throughout the book. Each chapter starts with a table containing the local notation employed therein. The symbols in common among the chapters are tabled within the associated list at the beginning of this book. Further, each chapter starts with a brief introduction presenting the addressed problem. A discussion related to achieved results, limitations, open problems, and possible future directions closes the chapter.

The perception and control problems addressed in this book are challenging research topics dealing with nonprehensile dynamic manipulation. Nonetheless, these topics are shared with other research domains such as soft robotics, legged systems, wearable robotics. This is ideally in line with the spirit of the blue-sky research funded by the European Research Council under the Advanced Grant agreement number 320992 which is here gratefully acknowledged. For this reason, this book not only represents the apex of the RoDyMan project, but it can be used as a reference source for undergraduates and Ph.D. students willing to start a research program in the robotic nonprehensile manipulation domain and the related topics, understand the already developed work, and have a view about the associated open challenges.

As a final word, the RoDyMan project culminating with this volume is meant as a tribute to Naples, the hosting city of the project, an avant-garde city in robotics technology, automation, gastronomy, and art culture.

Naples, Italy
August 2021

Bruno Siciliano
Fabio Ruggiero

Contents

Contributors

Alejandro Donaire The University of Newcastle, Callaghan, NSW, Australia

Alejandro Gutierrez-Giles CECAv-UNAM, Ciudad Universitaria, CDMX, Mexico

Jung-Tae Kim MIKNMEK Inc., Gyeongsangbuk-do, Republic of Korea

Vincenzo Lippiello Department of Electrical Engineering and Information Technology, PRISMA Lab, CREATE Consortium & University of Naples Federico II, Naples, Italy

Midhun S. Menon OLA Electric, Bangalore, India

Antoine Petit Therenva, Rennes, France

Fabio Ruggiero Department of Electrical Engineering and Information Technology, PRISMA Lab, CREATE Consortium & University of Naples Federico II, Naples, Italy

Aykut C. Satici Boise State University, Boise, USA

Bruno Siciliano Department of Electrical Engineering and Information Technology, PRISMA Lab, CREATE Consortium & University of Naples Federico II, Naples, Italy

Acronyms

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AABB	Axis-aligned bounding boxes
AR	Augmented reality
BnB	Ball-and-beam
BRISK	Binary robust invariant scalable keypoints
B-spline	Basis spline
BVP	Boundary value problem
CGAL	Computational geometry algorithms library
CLIK	Closed-loop inverse kinematics
CoM	Center of mass
CPU	Central processing unit
CUDA	Compute unified device architecture
DCC	Differential contact constraint
DC-PBD	Doubly-constrained position-based dynamics
DFSPH	Divergence-free smooth-particle hydrodynamics
DLO	Deformable linear object
DoD	Disk-on-disk
DoF	Degree of freedom
DVH	Diffused vortex hydrodynamics
EFL	Exact feed-forward linearization
FAST	Features from accelerated segment test
FDM	Finite difference method
FEM	Finite element method
FLin	Feedback linearization
FLIP	Fluid implicit particle
FTL	Follow the leader
FVM	Finite volume method
Gb	Gigabyte
GHz	Gigahertz

GMM	Gaussian mixture model
GPU	Graphics processing unit
GSM	Gradient smoothing method
ICP	Iterative closest point
IDA	Interconnection and damping assignment
IISPH	Implicit incompressible smooth-particle hydrodynamics
ISPH	Incompressible smooth-particle hydrodynamics
K-BKZ	Kaye–Bernstein-Kearsley-Zapas
KE-ME	Kinetic energy matching equation
k-NN	k-nearest neighbours
LUT	Lookup table
MAC	Marker-and-cell
MFC	Microsoft foundation class library
MJED	Multiplicative Jacobian energy decomposition
MPM	Material point method
MSER	Maximally stable extremal regions
MuJoCo	Multi-joint dynamics with contact
NURBS	Non-uniform rational B-spline
ODE	Ordinary differential equation
OS	Operating system
PBC	Passivity-based control
PBDM	Position-based dynamics method
PBFM	Position-based fluid method
PCA	Principal component analysis
PCG	Preconditioned conjugate gradient
PCISPH	Predictive-corrective incompressible smooth-particle hydrodynamics
PDE	Partial differential equation
PE-ME	Potential energy matching equation
pH	Port-Hamiltonian
PIC	Particle-in-cell
PID	Proportional–integral–derivative
PSPH	Projection smoothed-particle hydrodynamics
QR	Quick response
RGB	Red Green Blue
RGB-D	Red Green Blue Depth
RMSE	Root-mean-square error
SIFT	Scale-invariant feature transform
SOFA	Simulation Open Framework Architecture
SPH	Smoothed-particle hydrodynamics
S-R-S	Spherical-Revolute-Spherical
SURF	Speeded up robust features
TWMM	Two-wheeled mobile manipulator
WCSPH	Weak compressible smooth-particle hydrodynamics
ZMP	Zero moment point

Common Symbols

$[\mathbf{f}(\mathbf{x}), \mathbf{g}(\mathbf{x})]$	Lie bracket of two vector fields $\mathbf{f}(\mathbf{x})$ and $\mathbf{g}(\mathbf{x})$, with $\mathbf{x} \in \mathbb{R}^n$
$\otimes$	Kronecker product of matrices
∇	Divergence operator
$\|\mathbf{x}\|_{\mathbf{A}} = \mathbf{x}^T \mathbf{A} \mathbf{x}'$	Short way for the quadratic form
$\| \cdot \|$	Cartesian norm
0_n	The zero vector of dimension n
$\mathbf{A} \in \mathbb{R}^{n \times m}$	$\mathbf{A}$ is a $(n \times m)$ matrix of real numbers
$\mathrm{a}d_{\mathbf{f}}^{k}\mathbf{g}(\mathbf{x})$	Short way to indicate the Lie bracket $[\mathbf{f}(\mathbf{x}), \mathrm{a}d_{\mathbf{f}}^{k-1}\mathbf{g}(\mathbf{x})]$, with $k > 0$
$\mathrm{d}iag([a_1 \cdots a_n])$	Definition of a diagonal matrix through a vector specifying its main diagonal
$\mathbf{I}_n \in \mathbb{R}^{n \times n}$	Identity matrix of dimension n
$L_{\mathbf{x}}\lambda(\mathbf{x})$	Lie derivative of a real valued function $\lambda(\mathbf{x})$ and a vector field $\mathbf{f}(\mathbf{x})$, with $\mathbf{x} \in \mathbb{R}^n$
$\mathbf{O}_n$	The square zero matrix of dimension n
$\mathbf{O}_{n \times m}$	The $(n \times m)$ zero matrix
$\mathbb{R}$	Set of real numbers
$SE(3)$	Special Euclidean group of dimension three
$\mathfrak{so}(3)$	Lie algebra of $SO(3)$
$SO(3)$	Special orthogonal group of dimension three
$t \in \mathbb{R}$	Time variable
$\mathcal{W}$	World-fixed inertial frame
$< \mathbf{x}, \mathbf{y} >$	Another way to indicate $\mathbf{x}^T\mathbf{y}$, where $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$
$\mathbf{x} \times \mathbf{y}$	Cross product between the vectors $\mathbf{x}, \mathbf{y} \in \mathbb{R}^2$ or $\mathbf{x}, \mathbf{y} \in \mathbb{R}^3$
$\mathbf{x} \in \mathbb{R}^n$	$\mathbf{x}$ is a $(n \times 1)$ vector of real numbers