Springer Tracts in Advanced Robotics 79

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STAR (Springer Tracts in Advanced Robotics) has been promoted under the auspices of EURON (European Robotics Research Network)

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Experimental Robotics

The 12th International Symposium on Experimental Robotics

Springer

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ISSN 1610-7438 ISSN 1610-742X (electronic)
ISBN 978-3-642-28571-4 ISBN 978-3-642-28572-1 (eBook)
DOI 10.1007/978-3-642-28572-1
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012937642

Printed on acid-free paper

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

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.

Since its inception, the *International Symposium on Experimental Robotics* (ISER) was published by Springer. Since the four past editions, ISER has found a more suitable home under STAR, together with other thematic symposia devoted to excellence in robotics research.

The Twelfth edition of *Experimental Robotics* edited by Oussama Khatib, Vijay Kumar and Gaurav Sukhatme offers in its eight-chapter volume a collection of a broad range of topics in field and human-centered robotics. The contents of these contributions represent a cross-section of the current state of robotics research from one particular aspect: experimental work, and how it reflects on the theoretical basis of subsequent developments. Experimental validation of algorithms, concepts,

or techniques is the common thread running through this large collection of widely diverse contributions, spanning from calibration to grasping and manipulation, from novel sensors and actuators to locomotion and multirobot systems, from robot modelling and object modeling to mapping and tracking, from human-robot interaction to medical and assistive robotics.

From its warm social program to its excellent technical program, ISER culminates with this unique reference on the current developments and new directions of experimental robotics – kudos to the organizers of the symposium and the editors of this book!

December 2011
Naples, Italy

Bruno Siciliano
STAR Editor

Preface

The International Symposium on Experimental Robotics (ISER) is a series of biennial symposia which began in 1989, and is sponsored by the International Foundation of Robotics Research (IFRR). ISER emphasizes experimental work while providing the robotics community with a forum for presenting research driven by creative ideas, bold visions, new systems, and novel applications of robotics. The tradition in ISER is to foster scholarly work that either addresses validation of theoretical paradigms through careful experimentation or contributes to the creation of novel experimental platforms that in turn inspire new theoretical developments. The ISER symposia are conceived to bring together in a small group setting researchers from around the world who are at the forefront of experimental robotics research, to assess and share their views and ideas about the state of the art, and to discuss promising new avenues for future research exploration in experimental robotics. The ISER meetings are organized around oral and interactive technical presentations in a single-track format.

The Twelfth Symposium was held on December 18–21, 2010 in New Delhi and Agra, India. The symposium was chaired by Oussama Khatib (Stanford University, USA), Vijay Kumar (University of Pennsylvania, USA), and Gaurav Sukhatme (University of Southern California, USA). The local organizing committee was chaired by Amarjeet Singh (Indraprastha Institute of Information Technology, Delhi) and Sudipto Mukherjee (Indian Institute of Technology, Delhi). The International Steering Committee for ISER is chaired by Oussama Khatib and includes Marcelo Ang (Singapore), Herman Bruyninckx (Belgium), Alicia Casals (Spain), Raja Chatila (France), Peter Corke (Australia), Eve Coste-Maniere (France), John Craig (USA), Paolo Dario (USA), Vincent Hayward (Canada), Gerd Hirzinger (Germany), Yoshihiko Nakamura (Japan), Paul Newman (UK), Daniela Rus (USA), Kenneth Salisbury (USA), Bruno Siciliano (Italy), Sanjiv Singh (USA), James Trevelyan (Australia), Tsuneo Yoshikawa (Japan), and Alex Zelinsky (Australia).

The program of the Twelfth Symposium included 64 technical papers, selected from open submission through a review process organized by the International Steering Committee. The symposium contributions report on a variety of new theoretical and experimental results, and point to new visions and trends in the field.

The topics of the technical sessions covered a broad spectrum of experimental robotics research activities. For the first time, 20 papers were presented in interactive format on electronic displays. The symposium sessions were Human-robot Interaction; Medical and Assistive Robotics; Calibration; Grasping and Manipulation; Motor Control and Locomotion; Robot Modeling, Object Modeling and Mapping; Mapping and Tracking; Multirobot Systems, Novel Sensors and Actuators. The program also included a special *marble session* overlooking the Taj Mahal. This was structured as a lively open-air, Oxford-style debate on whether robotics had lived up to its promise. The session (chaired by Bernie Roth) included five distinghuished panelists: Raja Chatila, Matt Mason, Brad Nelson, Roland Siegwart, and Sanjiv Singh.

This volume includes the complete collection of the contributions presented at the symposium, with authoritative introductions to each section by the chairs of the corresponding sessions. We are grateful to the authors and the participants who have all contributed to the success of this symposium by bringing an outstanding program, excellent technical presentations, and stimulating and insightful discussions. We would like also to express our thanks and gratitude to the local organizing team who created the perfect environment for fostering technical discussions and promoting intellectual debates in a relaxed setting.

December 23, 2010
New Delhi, India

Oussama Khatib, Stanford University
Vijay Kumar, University of Pennsylvania
Gaurav Sukhatme, University of Southern California

Session Summaries

I. Human-Robot Interaction

Authored by Session Chair, Wolfram Burgard, University of Freiburg

This section contained six papers covering several aspects of human-robot interaction including force-based, gesture-based, vision-based, and natural language-based interaction. The first paper, presented by Wilm Decre, described a robot programming approach for actively assisting humans in human-robot cooperation tasks. In this work, the operator and a robot jointly executed motions via force-based interaction. In experiments, the authors demonstrate that their approach leads to substantially lower human-robot interaction forces compared to classical admittance control. The second paper, authored by Wataru Takano and colleagues, presented an approach for humanoid robos to make linguistic inference by using language knowledge stored in a dictionary. The authors use this capability for associating motion patterns of humans. The third paper was presented by Thomas Kollar. Its contribution is a planning framework that enables robots to understand verbs of motion. The system follows natural language commands by finding a plan that minimizes a cost function which relates the language to the plan. In practical experiments, the authors demonstrate that their framework enables robots to robustly understand verbs of motion in natural language commands. In the fourth presentation, Amit Kumar Pandey described geometric and object-centered approaches to representing visibility and reachability. He also presented different application scenarios in which he demonstrates the usefulness of the approach. The fifth paper was presented by Nathan Koenig, who reported on different studies of the impact that the users visual access to the robot, or lack thereof, has on teaching performance in a learning from demonstration setting. The paper furthermore describes influence diagrams, a variant Bayesian networks, that support such settings by also representing the decision process in the graph structure. The final presentation of this session was given by Junaed Sattar about an approach for dealing with communication errors in human robot interaction. The authors propose an unconventional model for the risk of a system failure and of the associated recovery procedure that may be needed on the part of a human operator.

II. Medical and Assistive Robotics

Authored by Session Chair, Gaurav Sukhatme, University of Southern California?

Medical and assistive robotics has and continues to make an impact on our quality of life; from current commercial systems for assistive applications in examination and surgery to future control systems via neural interfaces. The papers in this session addressed different aspects of the field. The first paper, presented by Jaeheung Park, described an interface design and control strategies for a robot assisted ultrasonic examination system. The second paper, presented by Jaydev Desai, described the design and characterization of a novel discretely actuated steerable probe for percutaneous procedures. The paper proposes the use of shape memory alloy (SMA) actuators in the design exploiting their small size and high power density. Experiments demonstrated the local actuation of the steerable probe in a tissue simulant. The third paper, presented by Vogel and van der Smagt, described a system for the control of a robot by a human with Tetraplegia using a neural interface system. The goal of this work is to develop assistive technologies for people with severe physical disabilities. Preliminary experimental results show that with very little training, participants can perform simple interaction tasks with the environment. The fourth paper, presented by Alex Zelinsky, dealt with human-factors studies that go into enhancing automotive safety solutions. It describes a driver inattention warning system which has been developed for commercial applications, with an initial focus on heavy vehicle fleet management applications. A case study reporting a year-long real-world deployment of DSS showed the effectiveness of the technology in mitigating driver inattention. The fifth and final paper, presented by Kyle Gilpin was on novel actuation and exhibited the control of closed-chain robots with compliant SMA actuators. This paper presented algorithms, devices, simulations, and experimental results with a locomoting robot that uses compliant, sheet-based, SMA actuators. In addition to actuator characterization, the paper gives a practical implementation of a provably correct algorithm capable of generating locomotion gaits in closed-loop linkages.

III. Calibration

Authored by Session Chair, Nicholas Roy, Massachusetts Institute of Technology

Calibration is a critical but unheralded topic in robotics. With the advent of highly articulated robots carrying many different kinds of sensors, it is becoming an increasingly essential capability. The papers in this session addressed different calibration problems, including the basic problem of how to control a robot composed of non-rigid components. The first paper was presented by Mark Sheehan and addressed calibration of a set of laser range finders, to find a set of parameters describing the relative positions and orientations, as well as timing skews, that minimize the variance of the measurements in the produced point cloud. The problem is phrased as an optimization problem in terms of Rényi's quadratic entropy and leads to a very efficient calibration procedure generating very "crisp" laser point clouds. The second paper presented by Jesse Levinson addressed a very related problem, but used a Bayesian approach to modelling the data that allowed the model to also incorporate

non-geometric properties of the data. The authors used expectation-maximization to fit a Gaussian model of both laser geometry and laser beam remittance, allowing the system to self-calibrate sensor location, orientation and each beam's response to environment surfaces of different reflectivities. The third paper was presented by Gaurav Sukhatme and addressed the problem of simulataneous calibration of sensor position and timing. The authors introduced the Time Delay Interative Closest Point algorithm based on Rodrigues parameters. This representation allows the temporal calibration of different types of sensors to be treated as a registration problem, and requires only small amounts of data and demonstrates fast, accurate and reliable convergence. The fourth paper was presented by Vijay Pradeep, and presented a general-purpose framework for calibrating both the sensors and actuators of a robot. The authors show how measurements can be propagated along a kinematic chain, incorporating uncertainties in the link parameters, formulating the sensor and kinematic calibration as a least-squares minimization based on measurements alone. Finally, Nikolaus Correll presented the fifth paper describing a class of soft mechanisms that can undergo shape change and locomotion under pneumatic actuation. The authors both describe the physics of active elasticity that allows distributed actuation embedded inside the body of a flexible robot, but also how miniature pneumatic valves, sensors, and microcontrollers can be embedded for each cell into the silicone actuator, leading to distributed computation and control and suggesting a basis for a new generation of biomimetic soft robot systems.

IV. Grasping and Manipulation

Authored by Session Chair, Jaydev Desai, University of Maryland

The papers presented in this session were in the area of grasping and manipulation of objects from micro-scale to macro-scale. In the realm of macro-scale manipulation, Kaijen Hsiao presented the paper on manipulation of household objects using sampling-based planning techniques which combined with collision detection, enables the PR2 robot to plan the desired poses for grasping and moving objects. In this work, reactive grasping strategy was executed and the robustness of the approach was demonstrated for two pick-and-place operations on each of the fifteen objects. In the paper presented by Adam Leeper, near-field stereo vision technique was used to improve the grasping task. The key idea of this approach was the use of a feature-based cost function on local 3D data to evaluate the feasibility of a proposed grasp. The proposed technique was demonstrated for grasping in cluttered environments. Paul Pounds presented the paper in the area of aerial grasping from a helicopter UAV platform. The grasping and retrieval problem was split into six sub-problems. He argued that rigid manipulators for grasping were not optimal for such tasks and hence adaptive and compliant grasping would provide better performance. His work also demonstrated grasping in the hovering mode. Alberto Rodriguez presented the paper on demonstrating the manipulation capabilities with compliant simple hands. His work explored the trade-off between generality and practicality of grasping and demonstrated blind grasping in a bin using three and

four fingers. Finally, Bradley Kratochvil demonstrated manipulation of objects at the micro-scale using magnetic fields. The novelty of this approach was the linear superposition of the field contributions when the cores are kept within their linear magnetization regions as well as the ability to attach this manipulation system to an inverted microscope. He demonstrated the system by microassembly of pegs into matching holes in the sidewalls.

V. Motor Control and Locomotion

Authored by Session Chair, Daniela Rus, Massachusetts Institute of Technology

The Motor Control and Locomotion session introduced six state-of-the-art results in motor control for locomotion and manipulation, with a focused emphasis on adaptation and learning to enable operation under challenging situations ranging from playing table tennis to flying with aggressive maneuvers and manipulating tools of various types.

This first paper, "Interaction Force, Impedance, and Trajectory Adaptation: by Humans for Robots", starts with the observation that humans pose a remarkable ability to adapt and interact with external environments and internal dynamics by tuning the force and impedance of limbs. This allows humans to perform a wide range of tasks such as holding an egg or hammering a nail. The motor commands for the muscles involved in human or robot motion have both feed-forward and feedback terms, both of which can be adapted during movement. The paper proposes a model for the dynamics of a rigid body model of the arm interacting with the environment that can achieve simultaneous interaction force, impedance, and trajectory adaptation and can deal with unstable situation. Experiments dome in simulation and with the DLR 7 degree of freedom light weight robot support this point. This novel way to control a robot has a range of applications in human-robot interactions such as rehabilitation, physical training, and teleoperations.

The second paper, "Experiment with Motor Primitives to Learn Table Tennis", the challenging task of playing table tennis is used as an example to demonstrate an algorithm that relies on low-level motion primitives to synthesize a complex real-time adaptive controller. Skill learning algorithms are first used to acquire the control for the the striking and hitting motion primitives and for acquisition by imitation. A reinforcement learning algorithm based on relative entropy policy search is then used to compose the basic motions. The algorithms were demonstrated using a Barrett 7DOF WAM arm show the power of the algorithm. For example the ball can be hit successfully at many different locations using generalized forehands. The opposing partner is a ball launcher operating at 3m/s and the return strike is at 8m/s.

The third paper, "Trajectory Generation and Control for Precise Aggressive Maneuvers with Quadrotors", considers the challenge of designing trajectories in a 12-dimensional state space using an underactuated robot with 4 actuators. A system model is developed from first principles and feedback control laws are developed for a family of trajectories defined as a sequence of segments, each with a controller parameterized by a goal state. The sequence consists of 5 phases: hover control

(still) to a desired position, control to a desired velocity vectors, control to a desired pitch angle, control to zero pitch angle, and hover control (soft) to a desired position. Phases 1, 2, and 3 control the maneuver. Phases 4 and 5 are recovery phases. The controller has impressive performance demonstrated experimentally by flying downward and upward through both horizontal and vertical openings.

The fourth paper, "Improved stability of Running over Unknown Rough Terrain via Prescribed Energy Removal", describes a novel feed-forward actuation scheme for legged robots in which energy is actively removed during a portion of each stride to maximize stability. The algorithm was tested on a single leg hopping robot capable of sagittal plane locomotion. This work demonstrates for the first time on a physical platform the active energy removal controller. Quantitatively, the data form the experiments shows good correlation with the model. Qualitatively, the experiment shows consistent rapid recovery from step perturbations.

The fifth paper, "On the Comparative Analysis of Locomotory Systems with Vertical Travel" considers a dimensionless measure of locomotive efficiency called specific resistance which is often used to compare the transport cost of vehicles for the vertical domain which includes vertical climbing robots and UAVs. Specific resistance is defined as the power required to keep a vehicle in motion divided by the weight and the velocity of travel, and abstracts away the details of locomotion into a single number. This study provides foundations for comparing various strategies that have a vertical locomotion component. By comparing data from several platforms, the work concludes that linear models provide good methods for comparison, although in some cases higher-order models are required.

The sixth paper, "Planning and Control of a Humanoid Robot for Navigation on Uneven Multi-scale Terrain", describes a humanoid navigation system capable of stepping over terrain with geometric uncertainty on the order of a few centimeters. The system includes a footstep planning module, a walking balance module, a free leg trajectory module, and an interactive navigation system that allows humans to input trajectories. Experiments carried with the full-sized humanoid HRP-2 look promising.

These six papers enable complex and sophisticated locomotion and manipulation robot capabilities. The controllers involve novel theory validated by hardware. The results are exciting and bring us closer to the dream of natural human-robot interactions in human-centered activities and environments.

VI. Robot Modeling, Object Modeling and Mapping

Authored by Session Chair, Salah Sukkarieh, University of Sydney

The papers presented in this session were focussed in the general area of perception related to the modelling of robots and/or the environment that they operate within. The first paper was presented by Forest Rogers-Marcovitz from CMU and dealt with the problem of identifying vehicle motion models in real time. The presentation discussed work which focussed on generating parameterised slip models

that capture the vehicle error dynamics, which can then be used to predict trajectories given control inputs on various terrain. Results from skid-steer and Ackerman vehicles were presented. The second paper was presented by John Rogers from GTech which experimentally explored the relationship between SLAM performance and sensor accuracy, focussing specifically on laser sensors for micro-robots. Various laser systems were tested in an indoor environment. The third paper was presented by Joseph Djugash from CMU. The presentation focussed on work that was carried out to test in detail the authors algorithm for simultaneously determining the location of stationary and mobile sensors in a network that comprised of only range sensing and odometry. The algorithm is based on a multi-hypothesis Gaussian distribution filter, and experiments were conducted using a number of stationary ranging nodes and an autonomous wheelchair with a ranging node. The fourth paper was presented by Ralf Kaestner from ETH and looked at learning spatial representations of dynamic environments using 3D laser points generated by a tilting 2D laser scanner. The formulation used Gaussian Mixture models and cell decomposition, along with sequential algorithm to learn the model parameters. Tests where conducted in different structured outdoor environments with dynamic objects moving about. The fifth paper was presented by Peter Henry from UW and discussed the use of RGB-D cameras for building dense 3D images of indoor environments. The presentation discussed a specific algorithmic implementation which jointly optimises visual features and shape-based alignment, along with view-based loop closure and pose optimisation. This achieved both a locally and globally consistent map (a combination of ICP, SIFT and RANSAC). Several experiments using an RGB-D camera in an indoor environment were conducted. The final paper was presented by Matthew Walter from MIT. Work was presented on the use of visibility hypotheses based on 2D construction of visual keypoints based on a RANSAC methodology. The inputs are provided by a human who guides the robots. Experiments were conducted using an autonomous forklift which was guided and told of various objects. The system built up multi-view appearance models of the objects online, and demonstrated effective results despite different visual changes in the environment.

VII. Mapping and Tracking

Authored by Session Chair, Dieter Fox, University of Washington

The papers presented in this session covered novel mapping techniques for a wide range of platforms and environments, including aerial and ground vehicles, surface vessels, and underwater vehicles. Mitch Bryson presented a paper describing how unmanned aerial vehicles can be applied to ecology monitoring by mapping large outdoor terrains. The work combines GPS data with an IMU and a monocular camera to generate accurate 3D terrain models and automatically detect and classify different species of trees based on the visual data. The paper presented by Jacques Leedekerken introduces a framework for simultaneously mapping terrestrial and subsurface environments using an autonomous surface craft. The approach, which integrates several sensor modalities into memory-efficient octree maps, successfully

generated maps of portions of the Charles River and surrounding structures such as bridges and buildings. Jnaneshwar Das presented a technique for simultaneously tracking and sampling dynamic oceanic features such as algal bloom. By planning the survey paths of an autonomous underwater vehicle in the reference frame of the moving oceanic feature, the approach was able to track and survey a drifting patch for a period of seven days. The work presented by Steven Dubowsky gained substantial attention due to the recent collapse of the offshore oil-drilling platform Deepwater Horizon. Steven showed that it is possible to map underwater 3D structures using a robotic manipulator solely equipped with joint encoders; thereby making the mapping approach applicable even under very harsh conditions. Laurent Kneip presented a paper on mapping with micro aerial vehicles. He introduced a filtering approach that combines inertial and vision data while being robust to time delays and dropouts due to wireless data transmission. The last talk of the session was given by Bertrand Douillard, who presented a paper describing an efficient pipeline for segmentation and classification of 3D point clouds. In addition to discussing various 3D features, the paper provides experimental evaluations of a ground plane and object segmentation method and a template based classification approach using ICP as a distance measure.

VIII. Multirobot Systems, Novel Sensors and Actuators

Authored by Session Chair, Sanjiv Singh, Carnegie Mellon University

The papers in this session combined multiple topics. The first paper was presented by Dinesh Manocha on coordination and navigation of multiple differentially driven robot in such a way as to respect both kinematics and dynamical constraints. Specifically, the work reported adds an acceleration constraint to the standard method that respects curvature-velocity constraints only. Results from 5 robots operating in tight proximity were shown. The second paper was presented by Gregory Mermoud on model-based synthesis of distributed controllers for multirobot systems. The authors have investigated both bottom-up and top-down methods and experimental results from both methods were compared. Nathan Michael presented the third paper that showed both analytically and experimentally that the control gain, network update rate, as well as the communication and control graph topologies are critical for determining the stability of networked robots. He used the experimental platform consisting of quadrotors to understand the effect of time delays on the stability of network controlled robots. He also showed that the instability in the network is due to the presence of cycles in the control graph. Caleb Rucker presented the final paper on the modeling of continuum (snake like) mechanisms. The specific question addressed in the presentation is on how to model such devices when loads are applied. A key application is to estimate the loading given the measurements in the joints.

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