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Distributed Autonomous Robotic Systems

The 12th International Symposium

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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: 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.

DARS is a well-established single-track conference that gathers every 2 years the main researchers in *Distributed Autonomous Robotic Systems*. Since the 10th edition in 2010, STAR has welcomed DARS among the volumes resulting from thematic symposia devoted to excellence in robotics research.

The volume edited by Nak Young Chong and Young-Jo Cho offers in its 32 chapters an interdisciplinary collection of technologies, algorithms, system architectures, and applications of advanced distributed robotic systems. The contents are effectively grouped into four thematic sections: collaborative exploration, localization, and mapping; cooperative manipulation and task allocation; formation control and path planning; multi-robot communication and control architecture.

Rich by topics and authoritative contributors, the 12th edition of DARS in 2014 culminates with this unique reference on the current developments and new directions in the field of distributed autonomous robotic systems. A very fine addition to STAR!

Naples, Italy
August 2015

Bruno Siciliano
STAR Editor

Preface

The latest volume in the Distributed Autonomous Robotic Systems series constitutes the thoroughly reviewed post-conference proceedings of the 12th International Symposium on Distributed Autonomous Robotic Systems (DARS 2014), which was held at the Daejeon Convention Center, Daejeon, Korea, November 2–5, 2014. Following the tradition established by the previous symposiums since 1992, the goal of DARS 2014 has been to exchange and stimulate research ideas to realize advanced distributed robotic systems. Distributed robotics is a rapidly growing, interdisciplinary research area lying at the intersection of computer science, communication and control systems, and electrical and mechanical engineering. Stunning examples of cutting-edge technologies, algorithms, system architectures, and applications were presented and discussed during a single-track, three-day symposium. Building on the momentum of successful previous symposiums, DARS 2014 also provided a supportive and exciting environment for academics and practitioners to present and discuss their novel theoretical results, implementations, and applications in distributed autonomous robotic systems.

DARS 2014 received a total of 81 papers from 11 countries. Sixty papers were submitted to the regular paper track and 21 papers were submitted to the work-in-progress paper track. For the first time in the history of DARS, the work-in-progress poster session was designed to allow authors to present new challenges and directions, and early and emerging results from both academia and industry, providing a forum for the discussion of timely topics and promising yet still-undeveloped ideas. This effort will further push the boundaries of our scientific and technical limits and expand the horizons of DARS beyond academia. The final technical program consists of 29 papers in a total of nine oral sessions and 25 papers in one poster session. The oral session provides a platform for authors to present and discuss their new findings and controversies in a formal way within a 20-minute time slot. The 80-minute poster session allows authors to facilitate more personal interactions with more targeted and interested audiences, and affords more time to present their work in depth.

Finally, 32 papers of the highest quality, carefully selected and revised after the symposium, are included in this volume. These papers will give a broad, yet focused perspective categorized into the following four areas: (1) collaborative exploration, localization, and mapping, (2) cooperative manipulation and task allocation, (3) formation control and path planning, and (4) multi-robot communication and control architecture. Well-defined specific research problems in the respective topic areas are investigated and analyzed on theoretical grounds and experimental confirmation under real-world conditions. Specifically, this volume elaborates on "distributed autonomy" that is efficient and scalable compared to the best-known centralized algorithms in the literature, and envisions ways it can evolve to be more sustainable. The latest findings and implications learned from all of the above-mentioned areas will help readers understand how and why various forms of cooperative interactions emerge and flourish in distributed autonomous robotic systems, and push them into today's demanding applications and large-scale distributed systems. This volume will be of great use to postgraduate students, researchers, and practitioners wishing to study a range of current and emerging issues and specific topics in distributed autonomous robotic systems.

In addition to ten regular sessions centered on distributed autonomy themes, DARS 2014 was honored to have four distinguished plenary session speakers. The titles and abstracts of the plenary lectures are given below:

Distributed Systems for Urban Mobility

Professor Emilio Frazzoli, Massachusetts Institute of Technology, USA

The first part of this talk will concentrate on self-driving cars, and their impact on personal mobility in urban settings. Research and development on self-driving cars is currently very active, and cars able to drive safely and reliably without need for human supervision are no longer science fiction. Indeed, several companies and universities have demonstrated vehicles able to drive autonomously in traffic, in the process building social awareness and pushing the boundaries of current regulations and risk management practices. At this point, a natural question to ask is: what is the point of autonomous cars? Is autonomy indeed a transformative technology, with a potential to drastically redefine mobility? If so, in what ways, and when?

I will argue that the "killer app" for self-driving cars is car sharing, and will provide analytical guidelines and financial justification for the design of shared-vehicle mobility-on-demand systems. As a case study, we consider replacing all modes of personal transportation in a city such as Singapore with a fleet of shared automated vehicles, able to drive themselves, e.g., to move to a customer's location. Using actual transportation data, our analysis suggests a shared-vehicle mobility solution can meet the personal mobility needs of the entire population with a fleet whose size is approximately one-third of the total number of passenger vehicles currently in operation.

The second part of the talk will concentrate on distributed algorithms for traffic signal control. The proposed algorithms are adapted from backpressure routing, which has been mainly applied to communication and power networks. Our algorithm ensures global optimality as it leads to maximum network throughput even though the controller is constructed and implemented in a completely distributed manner. Simulation results show that our algorithm significantly outperforms state-of-the-art algorithms.

Multi-robot Collision Avoidance and Applications

Professor Beom Hee Lee, Seoul National University, Korea

Nowadays, multi-robot operations are acknowledged as a common practice in industry for various tasks. The state of the art of multi-robot systems is described in the first statement. Multi-robot research issues are then discussed in terms of the operational strategies: centralized, distributed, and mixed operational schemes. Next, we show that one of the main issues in multi-robot operation is the problem of collision avoidance. We also show the importance of the collision avoidance problem in multi-robot operations. For multi-robot collision avoidance, a special tool, called the collision map, is introduced and applied to this problem. More deep analysis and investigation are presented for an application of the collision map. Various types of collision maps are then introduced with several possible applications. Also, robot path modification is viewed in terms of collision avoidance using the concept of the collision map. Various applications using the collision map are presented for a problem of 100 multi-robot operations, a stealth intruder intercept scheme, and efficient multiple cleaning robots operation. Especially, the load balancing in multiple cleaning robots are realized using the collision map. Finally, future applications using multi-robot systems are briefly discussed.

Design and Navigation of Robots that Roll, Run, and Fly

Professor Roland Siegwart, ETH Zurich, Switzerland

Robots are rapidly evolving from factory workhorses, which are physically bound to their work-cells, to increasingly complex machines capable of performing challenging tasks as search and rescuing, surveillance and inspections, planetary exploration or autonomous transportation of goods. This requires robots to operate in unstructured and unpredictable environments and various terrains. This talk will focus on design and navigation aspects of wheeled, legged, swimming and aerial robots operating in complex environments. Our wheeled robots are designed to move on complex grounds or to autonomously drive in parking lots. For our quadruped walker we are researching optimal ways to exploit the natural dynamics and serial elastic actuation. Our swimming robots take inspiration from natural counterparts for optimal propulsion, and with our micro-helicopter projects we approach autonomous flights and inspections in cluttered and very narrow indoor environments as well as GPS-denied visual navigation in cities. And our small solar airplanes are capable of staying in the air indefinitely and flying close to the ground thanks to onboard vision.

A Synchronization Control Approach to Networked Robotic Systems

Professor Dong Sun, City University of Hong Kong, Hong Kong, China

Nowadays cooperative controls of networked robotic systems have become a hot research area with dramatically increased popularity. Synchronization is a common timekeeping methodology which requires the coordination of events to operate a system in unison. This talk will introduce our researches of using synchronization control approach to motion coordination of networked robots. The idea of synchronizing multiple coordinative robots to achieve a common goal is inspired by many examples found in nature. Our strategy is to control each robot to track along its desired trajectory while synchronizing its motion with the other robots to keep relative kinematics relationship as required by the coordination. To achieve this goal, we firstly pose the motion coordination problem as a synchronization control problem while defining the synchronization error based on the coordination requirement, and secondly we develop a synchronous controller that can guarantee both position and synchronization errors to approach zero asymptotically. Two case studies are conducted to demonstrate this synchronization approach. The first case study is to control formations of swarms of mobile robots to follow time-varying formations, with further extensions to various industrial applications such as coordination of multi-robot manipulators, multi-axis controls, and contouring error minimization of CNC machines. The second case study is to use a robotic cell manipulation system to transfer multiple biological cells in biomedical applications.

Furthermore, DARS 2014 had the Best Paper Award competition intended to recognize excellence among papers with substantial novelty and research contribution. The following papers were nominated in random order for the Best Paper Award by the Program Committee based on reviewer comments and scores.

- **Distributed Online Patrolling with Multi-Agent Teams of Sentinels and Searchers**
  Nicola Basilico[1], Timothy H. Chung[2], and Stefano Carpin[3]
  [1]University of Milan, Italy, [2]Naval Postgraduate School, USA, [3]University of California, USA
- **Human–Robot Collaborative Topological Exploration for Search and Rescue Applications**
  Vijay Govindarajan, Subhrajit Bhattacharya, and Vijay Kumar
  University of Pennsylvania, USA

- **Cooperative Mobile Robot Control Architecture for Lifting and Transportation of Any Shape Payload**
  B. Hichri[1], L. Adouane[2], J.-C. Fauroux[2], Y. Mezouar[2], and I. Doroftei[3]
  [1]Institut Pascal Clermont Ferrand, France, [2]Institut Pascal Clermont Ferrand, France, [3]Gheorghe Asachi Technical University of Iasi, Romania
- **A Repartitioning Algorithm to Guarantee Complete, Non-overlapping Planar Coverage with Multiple Robots**
  Kurt Hungerford[1], Prithviraj Dasgupta[1], and K.R. Guruprasad[2]
  [1]University of Nebraska, USA, [2]National Institute of Technology, India
- **A Response Threshold Sigmoid Function Model for Swarm Robot Collaboration**
  Anshul Kanakia, John Klingner, and Nikolaus Correll
  University of Colorado, USA
- **Glider CT: Analysis and Experimental Validation**
  [1]Dongsik Chang, [2]Wencen Wu, and [1]Fumin Zhang
  [1]Georgia Institute of Technology, USA, [2]Rensselaer Polytechnic Institute, USA

The Best Paper Award went to Anshul Kanakia, John Klingner, and Nikolaus Correll for their paper "A Response Threshold Sigmoid Function Model for Swarm Robot Collaboration." The winner was decided during the symposium by the Award Committee based on the technical merit and significance of the paper and quality of presentation. Listed below are the Program Committee and Award Committee members.

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We would like to offer our sincere thanks to the Organizing Committee members (Chair, Dr. Young-Jo Cho, ETRI, Korea) for their hard work and outstanding contributions, and the Steering Committee members (Chair, Prof. Hajime Asama, The University of Tokyo, Japan) for their helpful guidance and support. Special thanks are extended to the Program Co-chairs (Prof. Jun Ota, The University of Tokyo, Japan, Prof. Fulvio Mastrogiovanni, the University of Genoa, Italy, and Prof. Timothy H. Chung, the Naval Postgraduate School, USA) for their time and effort in attracting and recruiting qualified Program Committee members and collecting high-quality papers. We would also like to express our deep appreciation to the Program Committee and Award Committee members for their hard work and dedication. They all devotedly struggled to shape and maintain the highest quality levels of the final program within a very tight time frame. Last but not least, we would further like to express our heartfelt thanks and appreciation to all the participants for their active engagement in the symposium program and all the contributing authors in this volume.

Both academics and practitioners are invited to enjoy the very essence of DARS 2014, full of innovative ideas and practical strategies for implementation!

Nak-Young Chong
Young-Jo Cho

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