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Distributed Autonomous Robotic Systems

The 10th International Symposium

Springer

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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.

DARS is a well-established single-track conference that gathers every two years the main researchers in *Distributed Autonomous Robotic Systems*. The papers from the last four editions have been published as edited collections by Springer. STAR is proud to welcome the Tenth edition of DARS among the volumes resulting from thematic symposia devoted to excellence in robotics research.

The volume edited by Alcherio Martinoli, Francesco Mondada, Nikolaus Correll, Grégory Mermoud, Magnus Egerstedt, M. Ani Hsieh, Lynne E. Parker and Kasper Støy offers in its forty-three chapters an interdisciplinary collection of technologies, algorithms, system architectures, and applications of advanced distributed robotic systems. The contents are effectively grouped into four thematic parts, each

introduced by an invited contribution by a world-renowned scholar in the field: Part I on distributed sensing, Part II on localization, navigation, and formations, Part III on coordination algorithms and formal methods, Part IV on modularity, distributed manipulation, and platforms.

Rich by topics and authoritative contributors, DARS 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 the series!

Naples, Italy
July 2012

Bruno Siciliano
STAR Editor

Preface

The goal of the Symposium on Distributed Autonomous Robotic Systems (DARS) is 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. Technologies, algorithms, system architectures, and applications were presented and discussed during a single-track, 3-day symposium. The 10th edition of DARS took place at the École Polytechnique Fédérale de Lausanne (EPFL), in its idyllic location on the shores of Lake Geneva, Switzerland. The symposium also included a great social event in the Lavaux, a UNESCO World Heritage Site, immersed in the beautiful fall colors, just at the end of the grape harvesting period. More details and pictures can be found on http://dars2010.epfl.ch.

DARS 2010 has been an excellent 10th anniversary edition thanks to the high quality of the submissions and selective reviewing process. We received a total of 75 submissions; 30 contributions were presented both orally and as a poster, while 13 uniquely as poster. Each submitted paper was reviewed by at least three reviewers and a technical program co-chair. The editors of this book—four technical program co-chairs (Magnus Egerstedt, M. Ani Hsieh, Lynne E. Parker, and Kasper Støy), two publication co-chairs (Grégory Mermoud and Nikolaus Correll), and two general co-chairs (Alcherio Martinoli and Francesco Mondada)—coordinated the review process with the help of the 99 members of the program committee. We are very grateful to all the reviewers and technical program co-chairs for their thoroughness and constructivism in reviewing the papers. All the accepted papers, including those presented only as poster, were included in the digital pre-proceedings distributed at the event and conditionally accepted for inclusion in this STAR volume, contingent to both presentation of the work at the symposium and proper addressing of the reviewers' and technical co-chairs' remarks. To this purpose authors were encouraged to submit a revised version after the conference together with a cover letter explaining how the reviewers' criticism was addressed. We noticed a drastic improvement in the quality of contributions due to the introduction of this second post-conference

quality control checkpoint; only a few authors were encouraged to take into account final minor suggestions and eventually all the revised papers were accepted in this volume. The overall collection consists therefore of 43 original contributions which are organized in four different parts, each introduced by a different technical program co-chair: distributed sensing (Part I); localization, navigation, and formations (Part II); coordination algorithms and formal methods (Part III); modularity, distributed manipulation, and platforms (Part IV). We feel that this breakdown is indeed representative of the current research activities in distributed robotics and is coarse enough to remain valid over the next few years.

The program of DARS 2010 included several invited keynote talks by world-renowned speakers representing well the four areas of distributed robotics mentioned above: Gaurav S. Sukhatme, University of Southern California for Part I; Raffaello D'Andrea, ETH Zurich and Kiva Systems for Part II; Radhika Nagpal, Harvard University for Part III; and Haruhisa Kurokawa, AIST for Part IV. We include in this volume abstracts and bio-sketches for each invited contribution and speaker, respectively.

DARS 2010 distributed two awards, one for the best student contribution and one for overall best contribution, co-sponsored by the DARS 2008 organizing committee, represented by Haruhisa Kurokawa at the symposium. The award panel was chaired by Hajime Asama (Tokyo University) and included Alan Winfield (University of West England), Radhika Nagpal (Harvard University), Haruhisa Kurokawa (AIST), James McLurkin (Rice University), and Magnus Egerstedt (Georgia Institute of Technology). The award selection process took into account various factors, including the reviewers' score, the revised contribution included in the digital pre-proceedings, the presentation, and related discussion at the symposium. The Best Paper Award was assigned to T.W. Mather, C. Braun and M.A. Hsieh (Drexel University) for their paper entitled "Distributed Filtering for Time-Delayed Deployment to Multiple Sites". The Best Student Paper Award was shared by two contributions, namely that of D. Mellinger, M. Shomin, N. Michael and V. Kumar (University of Pennsylvania) entitled "Cooperative Grasping and Transport using Multiple Quadrotors" and that of Y. Chen, X. C. Ding, A. Stefanescu and C. Belta (Boston University) entitled "A Formal Approach to Deployment of Robotic Teams in an Urban-Like Environment".

Last but not least, we would like to acknowledge the support of our partners in hosting DARS 2010. The Swiss National Science Foundation, the Swiss National Center for Competence in Research for Mobile Information and Communication Systems, the Swiss National Center for Competence in Research for Robotics, the Institute of Environmental Engineering at EPFL, and all of our industrial partners (BlueBotics SA, Cyberbotics S.à.r.l, GCtronic S.à.r.l, K-Team SA, and Skybotix S.à.r.l,) have financially co-sponsored the symposium, while the IEEE Robotics and Automation Society has been involved as technical co-sponsor. We would also like to thank the Editor-in-Chief of the STAR series, Bruno Siciliano, as well as Thomas Ditzinger, responsible coordinator of the series representing Springer Verlag, for affording us the opportunity to publish for the first time the proceedings of a DARS symposium in such prestigious venue. Finally, the symposium would not have been

possible without the hard work of a wonderful local organization team consisting of enthusiastic administrative assistants, PhD students, and research collaborators (see the DARS 2010 website for names and pictures).

We hope that this STAR volume will raise the same excitement and lively discussions that characterized the DARS 2010 symposium!

Lausanne, Switzerland
June 11, 2012

Alcherio Martinoli
Francesco Mondada
Nikolaus Correll
Grégory Mermoud

Invited Keynote Presentations

Termites, Starfish, and Robot Collectives

Radhika Nagpal *Harvard University, USA*

Abstract. Biological systems, from embryos to social insects, get tremendous mileage by having vast numbers of cheap and unreliable individuals cooperate to achieve complex goals. We are also rapidly building new kinds of distributed systems with similar characteristics, from multi-modular robots and robot swarms, to vast sensor networks. Can we engineer collective systems to achieve the kind of complexity and self-repair that nature seems to achieve? In this talk, I will describe several ongoing projects from my group where we use inspiration from nature – termites, starfish, and cells – to design collective robotic systems. For example, simple mobile robots that collectively build structures without explicit communication, self-adaptive modular robots that respond to the environment, and low-cost swarm robots that could self-assemble large-scale shapes. In each case, we use inspiration from biology to design simple decentralized cooperation, and techniques from computer science to analyze and generalize these algorithms to new tasks. A common theme in all of our work is understanding self-organizing multi-agent systems: how does robust collective behavior arise from many locally interacting agents, and how can we systematically program simple agents to achieve the global behaviors we want.

Biography. Radhika Nagpal is a Professor of Computer Science at Harvard University. She received her PhD degree in Computer Science from MIT, and spent a year as a research fellow at Harvard Medical School. She is a recipient of the 2005 Microsoft New Faculty Fellowship award, the 2007 NSF Career award and the 2010 Borg Early Career Award. Her research interests are biologically-inspired engineering principles for multi-agent systems and computational models multicellular biology.

Some Applications of Distributed Estimation and Control

Raffaello D'Andrea *ETH Zurich, Switzerland and Kiva Systems, USA*

Abstract. In this talk I will discuss several applications of distributed estimation and control: Kiva Systems, a company that uses hundreds of mobile robots to move inventory in distribution facilities; the Balancing Cube, a structure that can balance on any one of its edges or corners using six rotating mechanisms on the cube's inner faces; the Distributed Flight Array, a flying platform consisting of multiple autonomous single propeller vehicles that are able to drive, dock with their peers, and fly in a coordinated fashion; the Flying Machine Arena, a research-driven airspace where vehicles teach themselves – and each other – how to fly.

Biography. Raffaello D'Andrea is Professor of Dynamic Systems and Control at ETH Zurich and Technical Co-Founder of Kiva Systems, a company that develops adaptive and self-configuring warehouse automation systems using hundreds of networked, mobile robots. Also a creator of dynamic sculpture, he has shown his work at international venues including the Venice Biennale, the Luminato Festival, Ars Electronica, and ideaCity; two of his pieces are in the permanent collection of the National Gallery of Canada.

Survey of Modular Robotics as DARS Research

Haruhisa Kurokawa *AIST, Japan*

Abstract. Modular robotics has been widely researched over the past 20 years. Modular robots, especially self-reconfigurable ones, have many research topics in common with other research of DARS. Currently, however, most of the claimed prospects seem unfinished dreams. For example, only simple scalability has been obtained. Scalability and fault tolerance is far more difficult to attain by a physical system than an information system, and simple and quantitative scalability, even if attained, will not lead to qualitative one enabling graceful degradation. Joining forces of multiple modules is another difficult problem, though such an ability is indispensable to most robots. Applications of modular robots, especially of lattice-type systems, have not been clear. Endoluminal inspection and surgery will be a good application, but centralized or manual control is better suited for such. The history of modular robotics, with achievements and problems, can anyhow contribute to future DARS research such as in micro or nano scale, and the research, mainly ours, is surveyed in this talk.

Biography. Haruhisa Kurokawa received M.E. in Precision Machinery Engineering in 1981, and Dr. degree in Aeronautical and Astronautical Engineering in 1997, both from the University of Tokyo. He is currently Senior Researcher of the Field Robotics Research Group, Intelligent Systems Institute, National Institute of Advanced Industrial Science and Technology (AIST), Japan. He served as the general chair of DARS 2008. His main research subjects are kinematics of mechanisms, control in space, distributed autonomous systems and nonlinear control.

Monitoring the Coastal Ocean using Underwater Networked Robots: Algorithms and Experiments

Gaurav S. Sukhatme *University of Southern California, USA*

Abstract. We describe recent progress in systems and algorithms for underwater robots with applications to the monitoring of the coastal ocean. We describe a new algorithm for area coverage with a strong theoretical guarantee and a data fusion method for a communication-constrained underwater multi-robot system. Experimental results from sea trials (6 weeks) will be presented. We also give a brief overview of the underlying systems infrastructure that we have built to support the experiments and field trials.

Biography. Gaurav S. Sukhatme is a Professor of Computer Science (joint appointment in Electrical Engineering) at the University of Southern California (USC). He received his undergraduate education at IIT Bombay in Computer Science and Engineering, and M.S. and Ph.D. degrees in Computer Science from USC. He is the co-director of the USC Robotics Research Laboratory and the director of the USC Robotic Embedded Systems Laboratory which he founded in 2000. His research interests are in multi-robot systems, robot networks and aquatic robots. He has published over 200 papers in these and related areas. Sukhatme has served as PI on numerous NSF, DARPA and NASA grants. He is a Co-PI on the Center for Embedded Networked Sensing (CENS), an NSF Science and Technology Center. He is a senior member of the IEEE, and a member of AAAI and the ACM. He is a recipient of the NSF CAREER award and the Okawa foundation research award. He has served on many conference program committees, and is one of the founders of the Robotics: Science and Systems (RSS) conference. He was one of the program chairs of the 2008 IEEE International Conference on Robotics and Automation (ICRA) and is the program chair of the 2010 IEEE/RSJ Intelligent Robots and Systems (IROS) conference. He is the Editor-in-Chief of Autonomous Robots. He has served as Associate Editor of the IEEE Transactions on Robotics and Automation, the IEEE Transactions on Mobile Computing, and on the editorial board of IEEE Pervasive Computing.

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