# PROGRAM AT A GLANCE

## Sunday, November 6

<table>
<thead>
<tr>
<th>Time</th>
<th>Place: Council Room, 170 Queen’s Gate</th>
</tr>
</thead>
<tbody>
<tr>
<td>19:00 - 21:00</td>
<td>Welcome Reception and Registration</td>
</tr>
</tbody>
</table>

## Monday, November 7

<table>
<thead>
<tr>
<th>Time</th>
<th>Place: Flett Events Theatre &amp; Foyer, Natural History Museum</th>
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</thead>
<tbody>
<tr>
<td>08:30</td>
<td>Registration Open</td>
</tr>
<tr>
<td>09:00</td>
<td>Opening Speech</td>
</tr>
<tr>
<td>09:20</td>
<td><strong>Keynote Talk 1</strong>&lt;br&gt;James A. R. Marshall (University of Sheffield, UK)</td>
</tr>
<tr>
<td>10:20</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>10:40</td>
<td>Mo1: Distributed Coverage and Exploration</td>
</tr>
<tr>
<td>12:00</td>
<td>Preview of Poster Session 1</td>
</tr>
<tr>
<td>12:10</td>
<td>Mo2: Poster Session 1 &amp; Lunch</td>
</tr>
<tr>
<td>13:40</td>
<td>Mo3: Modular Robots and Smart Materials</td>
</tr>
<tr>
<td>14:40</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>15:00</td>
<td>Mo4: Multi-Robot Estimation</td>
</tr>
<tr>
<td>16:00</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>16:20</td>
<td>Mo5: Multi-Robot Systems in Applications I</td>
</tr>
<tr>
<td>17:20</td>
<td>End of Technical Program</td>
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</table>
### Tuesday, November 8

<table>
<thead>
<tr>
<th>Time</th>
<th>Place: Flett Events Theatre &amp; Foyer, Natural History Museum</th>
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<tbody>
<tr>
<td>08:30</td>
<td>Registration Open</td>
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<tr>
<td>09:00</td>
<td><strong>Keynote Talk 2</strong>&lt;br&gt;Vijay Kumar (University of Pennsylvania, USA)</td>
</tr>
<tr>
<td>10:00</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>10:20</td>
<td>Tu1: Multi-Robot Planning</td>
</tr>
<tr>
<td>11:40</td>
<td>Preview of Poster Session 2</td>
</tr>
<tr>
<td>11:50</td>
<td>Tu2: Poster Session 2 &amp; Lunch</td>
</tr>
<tr>
<td>13:20</td>
<td><strong>Keynote Talk 3</strong>&lt;br&gt;Katia Sycara (Carnegie Mellon University, USA)</td>
</tr>
<tr>
<td>14:20</td>
<td>Coffee Break</td>
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<tr>
<td>14:40</td>
<td>Tu3: Swarm Robotics I</td>
</tr>
<tr>
<td>16:00</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>16:20</td>
<td>Tu4: Multi-Robot Systems in Applications II</td>
</tr>
<tr>
<td>17:20</td>
<td>End of Technical Program</td>
</tr>
<tr>
<td>19:00 – 21:00</td>
<td>Banquet at Ognisko Restaurant</td>
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### Wednesday, November 9

<table>
<thead>
<tr>
<th>Time</th>
<th>Place: Flett Events Theatre &amp; Foyer, Natural History Museum</th>
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<tr>
<td>08:30</td>
<td>Registration Open</td>
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<tr>
<td>09:00</td>
<td><strong>Keynote Talk 4</strong>&lt;br&gt;Nikolaus Correll (University of Colorado Boulder, USA)</td>
</tr>
<tr>
<td>10:00</td>
<td>Coffee Break</td>
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<tr>
<td>10:20</td>
<td>We1: Multi-Robot Control</td>
</tr>
<tr>
<td>11:20</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>11:40</td>
<td>We2: Swarm Robotics II</td>
</tr>
<tr>
<td>12:40</td>
<td>Closing &amp; Awards</td>
</tr>
<tr>
<td>13:00</td>
<td>End of Conference</td>
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35 Sponsors
36 Exhibitors
On behalf of the Organizing and Advisory Committees, we welcome you to the 13th International Symposium on Distributed Autonomous Robotic Systems (DARS 2016). This time we are getting together in the famed Natural History Museum in London, United Kingdom, from November 7th to 9th, 2016. As one of the longest running symposia on distributed robotics, since 1992, we are proud to promote our developing field in a venue that represents the pinnacle of established sciences. We look forward to a stimulating exchange of ideas on the theory and practice of distributed autonomous robotic systems. As an interdisciplinary field we will have, among others, researchers from computer science, network science, control theory and electrical and mechanical engineering discussing their latest work on distributed robotics.

The program committee has been working hard to select the best contributions from a record of 120 submissions. With DARS being a single-track conference, we were able to accept 39% of submissions. Thirty of these will be presented in oral sessions from Monday to Wednesday and seventeen will be presented in two poster sessions on Monday and Tuesday. We have exciting and insightful papers on a broad range of topics, including distributed coverage and exploration, modular robots and smart materials, multi-robot control, multi-robot estimation, multi-robot planning, multi-robot systems in applications, and swarm robotics. We are confident that the single-track presentation format will encourage technical and in-depth presentations. In addition, you will enjoy four invited talks from researchers who are making a lasting contribution to science and robotics.

The success of this year’s symposium will be the result of the joint work of our program committee, organizing committee and advisory committee and the generous contributions from our sponsors. We would like to express our sincere gratitude for their efforts, as well as the contributions from all authors and the distributed robotics community at large. We believe their efforts have generated an exciting academic and social program. We hope you will enjoy DARS 2016.
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Nak Young Chong (JAIST, Japan)
Nikolaus Correll (University of Colorado Boulder, USA)
Rüdiger Dillmann (KIT, Germany)
Toshio Fukuda (Nagoya University, Japan)
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Alcherio Martinoli (EPFL, Switzerland)
Francesco Mondada (EPFL, Switzerland)
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Han-Lim Choi (KAIST, Republic of Korea)
Anders L. Christensen (University Institute of Lisbon, Portugal)
Timothy H. Chung (DARPA, USA)
Go to the Bee and Be Wise: Swarm Engineering Inspired by House-Hunting Honeybees

Abstract:
Distributed autonomous systems are likely to become increasingly important for robotics and other applications, due to their potential for resilience, scalability and flexibility. However, designing group-level behaviours that are implemented by simple individual-level rules operating with local information is an inherently hard problem, and guaranteeing properties of that behaviour is even harder. For example, search techniques and formal methods applied to swarms both rapidly fall foul of the curse of dimensionality as number of agents increases. However natural selection has successfully designed such systems repeatedly, and tools from the natural sciences have rigorously described the behaviour of very large systems of interacting components. In this talk I will recount how observations of house-hunting honeybees led to the design of a new class of distributed decision-making algorithm, and its deployment on hundreds of small and simple robots. Rather than simply imitating nature, however, the algorithm's principled development requires the integration of concepts and techniques from areas as diverse as behavioural ecology and statistical physics.

Biography:
James Marshall is Professor of Theoretical and Computational Biology at the University of Sheffield, where he is head of the Complex Systems Modelling Group in the Department of Computer Science, an affiliate member of the Evolution and Behaviour Research Group in the Department of Animal and Plant Sciences, and a member of Sheffield Robotics. After obtaining a Bachelors degree in Computer Science James combined doctoral studies into the evolution of cooperation with a career developing AI technology for computer games at Sony. He went on to postdoctoral positions at Imperial College London and the University of Bristol, then academic positions at Bristol and Sheffield. James’ interests are predominantly in animal behaviour, its evolution, and the interplay of these topics with engineering. He is the author of ‘Social Evolution and Inclusive Fitness: An Introduction’ (Princeton, 2015). His research into collective robotics is currently funded by the European Research Council, and his work on flying robots by a Programme Grant from the Engineering and Physical Sciences Research Council.
Coordination, Cooperation, and Collaboration in Multi-Robot Systems

Abstract:
The central challenge in multi-robot systems lies in the synthesis of collective behaviors which enable group performance that exceeds the ability of individuals. We explore three different paradigms for collective behaviors. At a fundamental level, coordination is beneficial when individuals are confronted with a task that they can complete but can do so more efficiently as a group. Cooperation refers to the ability of robots to accomplish tasks they could not have completed on their own. Collaboration is useful for groups with different types of robots with diverse capabilities and tasks which cannot be completed with a single type of robot. This talk will discuss biological inspiration for these paradigms, mathematical frameworks, and resilience in collective behaviors with applications to ground and aerial robots.

Biography:
Vijay Kumar is the Nemirovsky Family Dean of Penn Engineering with appointments in the Departments of Mechanical Engineering and Applied Mechanics, Computer and Information Science, and Electrical and Systems Engineering at the University of Pennsylvania.

Dr. Kumar received his Bachelor of Technology degree from the Indian Institute of Technology, Kanpur and his Ph.D. from The Ohio State University in 1987. He has been on the Faculty in the Department of Mechanical Engineering and Applied Mechanics with a secondary appointment in the Department of Computer and Information Science at the University of Pennsylvania since 1987.

Dr. Kumar served as the Deputy Dean for Research in the School of Engineering and Applied Science from 2000-2004. He directed the GRASP Laboratory, a multidisciplinary robotics and perception laboratory, from 1998-2004. He was the Chairman of the Department of Mechanical Engineering and Applied Mechanics from 2005-2008. He served as the Deputy Dean for Education in the School of Engineering and Applied Science from 2008-2012. He then served as the assistant director of robotics and cyber physical systems at the White House Office of Science and Technology Policy (2012-2013).

Dr. Kumar is a Fellow of the American Society of Mechanical Engineers (2003), a Fellow of the Institute of Electrical and Electronic Engineers (2005) and a member of the National Academy of Engineering (2013).


He is the recipient of the 1991 National Science Foundation Presidential Young Investigator award, the 1996 Lindback Award for Distinguished Teaching (University of Pennsylvania), the 1997 Freudenstein Award for significant accomplishments in mechanisms and robotics, the 2012 ASME Mechanisms and Robotics Award, the 2012 IEEE Robotics and Automation Society Distinguished Service Award, a 2012 World Technology Network Award, and a 2014 Engelberger Robotics Award. He has won best paper awards at DARS 2002, ICRA 2004, ICRA 2011, RSS 2011, and RSS 2013, and has advised doctoral students who have won Best Student Paper Awards at ICRA 2008, RSS 2009, and DARS 2010.

More information about Dr. Kumar’s research can be found in his TED talks.
Robust Human Control of Multi-Robot Swarms

Abstract:
As robotic platforms become cheaper and more reliable, multi-robot deployment becomes possible and desirable. Since complete robot autonomy for these deployments is not yet possible, the presence of a human operator is necessary. Multiple human studies have shown that cognitive limitations prevent effective human control of multi-robot systems of tens of robots. Another difficulty is that many different types of human interactions may be necessary to maintain and control multi-robot systems. Additionally, the coordination scheme of multiple robots can vary which has consequences on the operator’s difficulty of control. We have developed a characterization of human-robot tasks, and appropriate human robot interaction modes, based on the task’s cognitive complexity of control. This scheme helps explicate the forms of control likely to be needed and the demands they pose on human operators. This talk will present two lines of research following from this characterization. The first evaluates the potential for using scheduling techniques to improve the performance of systems in which operators must attend to multiple independently operating robots. The second presents challenges and results pertaining to human control of autonomously cooperating robotic swarms.

Biography:
Katia Sycara is a Professor in the Robotics Institute, School of Computer Science at Carnegie Mellon University and the Director of the Laboratory for Advanced Robotics and Semantic Web Technologies. She holds a B.S in Applied Mathematics from Brown University, M.S. in Electrical Engineering from the University of Wisconsin and PhD in Computer Science from Georgia Institute of Technology. She holds an Honorary Doctorate from the University of the Aegean. She is a Fellow of the IEEE, Fellow of the Association for the Advancement of Artificial Intelligence (AAAI), the recipient of the ACM/SIGART Agents Research Award and the recipient of the Research Award of the Group Decision and Negotiation section of the Institute of Operations Research and the Management Sciences (INFORMS). She has received multiple best paper awards and multimillion research grants. She has served as General Chair and Program Chair of multiple conferences, has given numerous invited talks, authored more than 600 technical papers dealing with multi-agent and multi-robot systems, human robot interaction, complex systems, negotiation, game theory, and data mining. She is a founding member of the International Foundation of Agents and Multiagent Systems (IFAAAMAS), and a founding member of the Semantic Web Science Association. She is a founding Editor-in-Chief of the journal “Autonomous Agents and Multiagent Systems” and is currently serving on the editorial board of 5 additional journals.
Material-Integrated Intelligence for Robot Autonomy

Abstract:
Advances in miniature electronics, distributed algorithms and manufacturing technology have enabled a new generation of smart composites that tightly integrate sensing, actuation, computation and communication. Such "robotic materials" are inspired by multi-functional natural structures such as the skin of the cuttlefish that can change its color and patterning, bird wings that can change their shape, or the human skin that provides tactile sensing at high dynamic range. I will describe a series of recent results that best illustrate the benefits of material integrated computation: high-bandwidth sensing for texture recognition and localization in artificial skins, distributed optimization for controlling shape change, distributed classification for recognizing gestures drawn onto a modular facade, and feedback control of soft robotic actuators. I will then describe current challenges in robotic grasping and manipulation, and demonstrate how robotic materials can provide critical sensing and control during a series of manipulation tasks with applications to warehouse automation, manufacturing and lab automation.

Biography:
Nikolaus Correll is an Assistant Professor in Computer Science at the University of Colorado at Boulder with courtesy appointments in Aerospace, Electrical and Materials Engineering. Nikolaus obtained a degree in Electrical Engineering from ETH Zurich in 2003 with visits at Lund Tekniska Hogskola, Sweden, and Caltech, and earned a PhD in Computer Science from EPFL in Lausanne, Switzerland in 2007 working with Alcherio Martinoli. He did a post-doc at MIT CSAIL from 2007-2009. Nikolaus is the recipient of a 2012 NSF CAREER award and a 2012 NASA Early Career Faculty Fellowship.
### Welcome Reception

**Sunday, 6th November**  
(19:00 – 21:00)  
The Welcome Reception takes place in the Council Room at 170 Queen’s Gate (London SW7 5HF) – a beautiful Victorian townhouse, completed in 1889.

### Lunch Sessions

**Monday, 7th November and Tuesday, 8th November**  
The poster & lunch sessions provide ample of opportunity to discuss the latest research and network. They take place in the foyer in front of the Flett Events Theatre, Natural History Museum. Lunch will be provided.

### Banquet

**Tuesday, 8th November**  
(19:00 – 21:00)  
The banquet takes place at Ognisko Restaurant (55 Exhibition Road, London SW7 2PN) – offering fine Polish cuisine in an impressive Victorian (1870s) townhouse.

### Closing & Awards

**Wednesday, 9th November**  
(12:40 – 13:00)  
Presentation of the DARS 2016 Awards (Flett Theatre, Natural History Museum).
###MONDAY, 7 NOV

####TECHNICAL PROGRAM

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<th>Time</th>
<th>Session</th>
<th>Details</th>
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<td>Keynote Talk 1</td>
<td>Go to the Bee and Be Wise: Swarm Engineering Inspired by House-Hunting Honeybees</td>
</tr>
<tr>
<td>10:40 - 12:00</td>
<td>Mo1: Distributed Coverage and Exploration</td>
<td>Session Chair: Sándor Fekete (TU Braunschweig, Germany)</td>
</tr>
<tr>
<td>Mo1-1</td>
<td>10:40 - 11:00</td>
<td>Information Based Exploration with Panoramas and Angle Occupancy Grids</td>
</tr>
<tr>
<td></td>
<td></td>
<td>¹Drexel University, USA, ²University of Pennsylvania, USA</td>
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<tr>
<td>Mo1-2</td>
<td>11:00 - 11:20</td>
<td>Communication-Restricted Exploration for Search Teams</td>
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<tr>
<td></td>
<td></td>
<td>University of Minnesota, USA</td>
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<td>Arizona State University, USA</td>
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<tr>
<td>Mo1-4</td>
<td>11:40 - 12:00</td>
<td>From Ants to Birds: A Novel Bio-Inspired Approach to Online Area Coverage</td>
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<tr>
<td></td>
<td></td>
<td>¹University of Bristol, UK, ²Bar-Ilan University, Israel</td>
</tr>
<tr>
<td>12:00 - 12:10</td>
<td>Preview of Poster Session 1</td>
<td>Session Chair: Bahar Haghighat (Ecole Polytechnique Fédérale de Lausanne, Switzerland)</td>
</tr>
<tr>
<td>12:10 - 13:40</td>
<td>Mo2: Poster Session 1</td>
<td></td>
</tr>
<tr>
<td>Mo2-1</td>
<td>Distributed Adaptive Locomotion Learning in ModRED Modular Self-Reconfigurable Robot</td>
<td>Ayan Dutta¹, Prithviraj Dasgupta¹ and Carl Nelson²</td>
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<tr>
<td></td>
<td></td>
<td>¹University of Nebraska at Omaha, USA, ²University of Nebraska-Lincoln, USA</td>
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<tr>
<td>Mo2-2</td>
<td>Effects of Spatiality on Value-Sensitive Decisions Made by Robot Swarms</td>
<td>Andrea Giovanni Reina¹, Thomas Bone¹, Vitto Trioni² and James A. R. Marshall¹</td>
</tr>
<tr>
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<td>¹University of Sheffield, UK, ²Italian National Research Council, Italy</td>
</tr>
<tr>
<td>Mo2-3</td>
<td>Evo-bots: A Simple, Stochastic Approach to Self-Assembling Artificial Organisms</td>
<td>Juan A. Escalera¹², Matthew Doyle¹, Francesco Mondada¹ and Roderich Grofi¹</td>
</tr>
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<td>¹University of Sheffield, ²University Carlos III of Madrid, Spain, ³Ecole Polytechnique Fédérale de Lausanne, Switzerland</td>
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<tr>
<td>Mo2-4</td>
<td>Evolving Group Transport Strategies for e-puck Robots: Moving Objects Towards a Target Area</td>
<td>Muhamad H. Mohammed Alkilabi¹², Aparajit Narayan¹, Chuan Lu¹ and Elio Tuci¹</td>
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<tr>
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<td>¹Aberystwyth University, UK, ²Kerbala University, Iraq</td>
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<tr>
<td>Mo2-5</td>
<td>From Formalised State Machines to Implementations of Robotic Controllers</td>
<td>Wei Li, Alvaro Miyazawa, Pedro Ribeiro, Ana Cavalcanti, Jim Woodcock and Jon Timmis</td>
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<td>University of York, UK</td>
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<tr>
<td>Mo2-6</td>
<td>Modelling Mood in Co-Operative Emotional Agents</td>
<td>Joe Colleton, Katie Atkinson, Daan Bloemergen and Karl Tuyls</td>
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<tr>
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<td>University of Liverpool, UK</td>
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<tr>
<td>Mo2-7</td>
<td>Multirobot Persistent Patrolling in Communication-Restricted Environments</td>
<td>Marta Romeo¹, Jacopo Banfi¹, Nicola Basilico¹ and Francesco Amigoni¹</td>
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<td>¹Politecnico di Milano, Italy, ²University of Milan, Italy</td>
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<tr>
<td>Mo2-8</td>
<td>Network Characterization of Lattice-Based Modular Robots with Neighbor-to-Neighbor Communications</td>
<td>André Nae², Benoit Piranda¹, Thadeu Tucci¹, Seth Copen Goldstein² and Julien Bourgeois³</td>
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<td>¹University of Bourgogne Franche-Comté, France, ²Carnegie Mellon University, USA</td>
</tr>
<tr>
<td>Mo2-9</td>
<td>Optical Wireless Communications for Heterogeneous DARS</td>
<td>Patricio I. Cruz, Christoph Hintz, Jonathan West and Rafael Fierro</td>
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<td>University of New Mexico, USA</td>
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### 13:40 - 14:40 | Mo3: Modular Robots and Smart Materials

Session Chair: Michael Rubenstein (Northwestern University, USA)

<table>
<thead>
<tr>
<th>Mo3-1</th>
<th>13:40 - 14:00</th>
<th>Geometrical Study of a Quasi-Spherical Module for Building Programmable Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Benoît Piranda and Julien Bourgeois</td>
<td>University of Bourgogne Franche-Comté, France</td>
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<table>
<thead>
<tr>
<th>Mo3-2</th>
<th>14:00 - 14:20</th>
<th>A Rule Synthesis Algorithm for Programmable Stochastic Self-Assembly of Robotic Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bahar Haghighat and Alcherio Martinoli</td>
<td>École Polytechnique Fédérale de Lausanne, Switzerland</td>
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</tbody>
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<thead>
<tr>
<th>Mo3-3</th>
<th>14:20 - 14:40</th>
<th>Distributed Camouflage for Swarm Robotics and Smart Materials</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Yang Li, John Klingner and Nikolaus Correll</td>
<td>University of Colorado Boulder, USA</td>
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</table>

### 15:00 - 16:00 | Mo4: Multi-Robot Estimation

Session Chair: Herbert G. Tanner (University of Delaware, USA)

<table>
<thead>
<tr>
<th>Mo4-1</th>
<th>15:00 - 15:20</th>
<th>Distributed Laplacian Eigenvalue and Eigenvector Estimation in Multi-Robot Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mehran Zareh, Lorenzo Sabattini and Cristian Secchi</td>
<td>University of Modena and Reggio Emilia, Italy</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Mo4-2</th>
<th>15:20 - 15:40</th>
<th>Distributed Object Characterization with Local Sensing by a Multi-Robot System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Golnaz Habibi, Sándor P. Fekete, Zachary Kingston and James McLurkin</td>
<td>1Rice University, USA, 2TU Braunschweig, Germany</td>
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</tbody>
</table>

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<thead>
<tr>
<th>Mo4-3</th>
<th>15:40 - 16:00</th>
<th>Construction of Optimal Control Graphs in Multi-Robot Systems</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Gal A. Kaminka, Ilan Lupu and Noa Agmon</td>
<td>Bar-Ilan University, Israel</td>
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### 16:20 - 17:20 | Mo5: Multi-Robot Systems in Applications I

Session Chair: Nathan Michael (Carnegie Mellon University, USA)

<table>
<thead>
<tr>
<th>Mo5-1</th>
<th>16:20 - 16:40</th>
<th>Formation Control of a Drifting Group of Marine Robotic Vehicles</th>
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<tbody>
<tr>
<td></td>
<td>Nicholas R. Rypkema and Henrik Schmidt</td>
<td>Massachusetts Institute of Technology, USA</td>
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<thead>
<tr>
<th>Mo5-2</th>
<th>16:40 - 17:00</th>
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<td>Chetan D. Pahlajani, Indrajit Yadav, Herbert G. Tanner and Ioannis Poullakakis</td>
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<td>Duane T. Davis, Timothy H. Chung, Michael R. Clement and Michael A. Day</td>
<td>1Naval Postgraduate School, USA, 2Defense Advanced Research Projects Agency, USA, 3Georgia Tech Research Institute, USA</td>
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## TUESDAY, 8 NOV

### TECHNICAL PROGRAM

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<td>Coordination, Cooperation, and Collaboration in Multi-Robot Systems</td>
<td>Vijay Kumar (University of Pennsylvania, USA)</td>
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<td>Dylan Shell (Texas A&amp;M University, USA)</td>
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<td>Robert Bosch GmbH, Germany, KTH Royal Institute of Technology, Sweden</td>
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<td>Informative Path Planning and Mapping with Multiple UAVs in Wind Fields</td>
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<td>Doo-Hyun Cho, Jung-Su Ha, Sujin Lee, Sunghyun Moon and Han-Lim Choi</td>
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<td>Clare Dixon (University of Liverpool, UK)</td>
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<td>Cinara Ghedini1, Carlos H. C. Ribeiro1 and Lorenzo Sabattini2</td>
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<td>Tu2-3</td>
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<td>Human Responses to Stimuli Produced by Robot Swarms - the Effect of the Reality-Gap on Psychological State</td>
<td>Gaëtan Podevin, Rehan O’Grady, Carole Fantini-Hauwel and Marco Dorigo</td>
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<td>HyMod: A 3-DOF Hybrid Mobile and Self-Reconfigurable Modular Robot and its Extensions</td>
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<td>Zijian Wang1, Guang Yang2, Xuanshuo Su2 and Mac Schwager2</td>
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<td>The Effectiveness Index Intrinsic Reward for Coordinating Service Robots</td>
<td>Yimon Douchan1 and Gal A. Kaminka2</td>
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<td>Triangular Networks for Resilient Formations</td>
<td>David Saldanha1, Amanda Prorok1, Mario F. M. Campos2 and Vijay Kumar1</td>
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<td>University of Pennsylvania, USA, Universidade Federal de Minas Gerais, Brazil</td>
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<td>Vertex: A New Distributed Underwater Robotic Platform for Environmental Monitoring</td>
<td>Felix Schill1, Alexander Bahr1 and Alcherio Martinoi1</td>
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<td>Ecole Polytechnique Fédérative de Lausanne, Switzerland, Hydromea SA, Switzerland</td>
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### 13:20 - 14:20  
**Keynote Talk 3**  
*Session Chair: Roderich Gross (University of Sheffield, UK)*  
**Robust Human Control of Multi-Robot Swarms**  
Katia Sycara (Carnegie Mellon University, USA)

### 14:40 - 16:00  
**Tu3: Swarm Robotics I**  
*Session Chair: Marco Dorigo (Université Libre de Bruxelles, Belgium)*

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| 14:40 - 15:00 | Tu3-1       | Discovery and Exploration of Novel Swarm Behaviors given Limited Robot Capabilities | Daniel S. Brown¹, Ryan Turner², Oliver Hennigh² and Steven Loscalzo²  
¹University of Texas at Austin, USA, ²Air Force Research Laboratory, USA |
| 15:00 - 15:20 | Tu3-2       | Towards Differentially Private Aggregation of Heterogeneous Robots    | Amanda Prorok and Vijay Kumar  
University of Pennsylvania, USA |
| 15:20 - 15:40 | Tu3-3       | Emergence and Inhibition of Synchronization in Robot Swarms           | Fernando Perez-Diaz, Stefan Trenkwalder, Ruediger Zillmer and Roderich Groß  
University of Sheffield |
| 15:40 - 16:00 | Tu3-4       | Programmable Self-Disassembly for Shape Formation in Large-Scale Robot Collectives | Melvin Gauci¹, Radhika Nagpal¹ and Michael Rubenstein²  
¹Harvard University, USA, ²Northwestern University, USA |

### 16:20 - 17:20  
**Tu4: Multi-Robot Systems in Applications II**  
*Session Chair: Sabine Hauert (University of Bristol, UK)*

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| 16:20 - 16:40 | Tu4-1       | Robust Coordinated Aerial Deployments for Theatrical Applications Given Online User Interaction via Behavior Composition | Ellen A. Cappo, Arjav Desai and Nathan Michael  
Carnegie Mellon University, USA |
| 16:40 - 17:00 | Tu4-2       | Distributed Convolutional Neural Networks for Human Activity Recognition in Wearable Robotics | Dana Hughes and Nikolaus Correll  
University of Colorado Boulder, USA |
| 17:00 - 17:20 | Tu4-3       | Construction Planning for Modularized Rail Structure – Type Selection of Rail Structure Modules and Dispatch Planning of Constructor Robots | Rui Fukui, Yuta Kato, Gen Kanayama, Ryo Takahashi and Masayuki Nakao  
University of Tokyo, Japan |
WEDNESDAY, 9 NOV
TECHNICAL PROGRAM

09:00 - 10:00  Keynote Talk 4  
Session Chair: Sabine Hauert (University of Bristol, UK)  
**Material-Integrated Intelligence for Robot Autonomy**  
Nikolaus Correll (University of Colorado Boulder, USA)

10:20 - 11:20  We1: Multi-Robot Control  
Session Chair: Lorenzo Sabattini (University of Modena and Reggio Emilia, Italy)

**We1-1**  
10:20 - 10:40  
Persistent Multi-Robot Formations with Redundancy  
Alyxander Burns¹, Bernd Schulze² and Audrey St. John²  
¹Mount Holyoake College, USA, ²Lancaster University, UK

**We1-2**  
10:40 - 11:00  
Chase your Farthest Neighbour: A Simple Gathering Algorithm for Anonymous, Oblivious and Non-Communicating Agents  
Rotem Manor and Alfred M. Bruckstein  
Technion, Israel

**We1-3**  
11:00 - 11:20  
A Comparative Study of Collision Avoidance Algorithms for Unmanned Aerial Vehicles: Performance and Robustness to Noise  
Steven Roelofsen, Denis Gillet and Alcherio Martinoli  
Ecole Polytechnique Fédérale de Lausanne, Switzerland

11:40 - 12:40  We2: Swarm Robotics II  
Session Chair: Amanda Prorok (University of Pennsylvania, USA)

**We2-1**  
11:40 - 12:00  
Decentralized Progressive Shape Formation with Robot Swarms  
Carlo Pinciroli¹, Andrea Gasparri², Emanuele Garone³ and Giovanni Beltrame⁴  
¹Worcester Polytechnic Institute, USA, ²Università Roma Tre, Italy, ³Université Libre de Bruxelles, Belgium, ⁴Polytechnique Montréal, Canada

**We2-2**  
12:00 - 12:20  
Evolving Behaviour Trees for Swarm Robotics  
Simon Jones, Matthew Studley, Sabine Hauert and Alan Winfield  
University of the West of England, UK

**We2-3**  
12:20 - 12:40  
Localization of Inexpensive Robots with Low-Bandwidth Sensors  
Shiling Wang¹, Francis Colas², Ming Liu³, Francesco Mondada⁴ and Stéphane Mignenat⁵  
¹ETH Zürich, Switzerland, ²INRIA Nancy - Grand Est, France, ³City University of Hong Kong, Hong Kong, ⁴Ecole Polytechnique Fédérale de Lausanne, Switzerland
AWARD FINALISTS

The following papers have been nominated for the Best Paper Award by the Program Committee.

[Mo3-1] Geometrical Study of a Quasi-Spherical Module for Building Programmable Matter
Benoît Piranda and Julien Bourgeois
University of Bourgogne Franche-Comté, France

[Mo3-3] Distributed Camouflage for Swarm Robotics and Smart Materials
Yang Li, John Klingner and Nikolaus Correll
University of Colorado Boulder, USA

[Tu3-1] Discovery and Exploration of Novel Swarm Behaviors given Limited Robot Capabilities
Daniel S. Brown¹, Ryan Turner², Oliver Hennigh² and Steven Loscalzo²
¹University of Texas at Austin, USA, ²Air Force Research Laboratory, USA

[Tu4-1] Robust Coordinated Aerial Deployments for Theatrical Applications Given Online User Interaction via Behavior Composition
Ellen A. Cappo, Arjav Desai and Nathan Michael
Carnegie Mellon University, USA

[Tu4-2] Distributed Convolutional Neural Networks for Human Activity Recognition in Wearable Robotics
Dana Hughes and Nikolaus Correll
University of Colorado Boulder, USA

Steven Roelofsen, Denis Gillet and Alcherio Martinoli
Ecole Polytechnique Fédérale de Lausanne, Switzerland
MONDAY, NOVEMBER 7

TECHNICAL PROGRAM DIGESTS
MONDAY, NOV 7 10:40 - 12:00

ORAL SESSION MO1

Session Chair: Sándor Fekete (TU Braunschweig, Germany)

Mo1-1 10:40 - 11:00

**Information Based Exploration with Panoramas and Angle Occupancy Grids**

Daniel Mox, M. Ani Hsieh
Drexel University, USA
Anthony Cowley, C. J. Taylor
University of Pennsylvania, USA

- We present a multi-robot information based exploration strategy with the goal of constructing high resolution 3D maps.
- We introduce the angle enhanced occupancy grid which takes into account the different perspectives a cell has been observed from and use it to plan where to collect RGBD panoramas.
- We demonstrate how our approach collects more relevant detail about the environment than traditional exploration methods.

Mo1-2 11:00 - 11:20

**Communication-Restricted Exploration for Search Teams**

Elizabeth A. Jensen, London Lowmanstone, and Maria Gini
University of Minnesota, USA

- In a disaster, environments may become unknown and dangerous.
- Communication lines are often limited due to destruction or high demand.
- A team of robots with local communication can explore to find points of interest.
- In our algorithms, as long as one robot survives, the exploration is guaranteed to be complete and the information passed to the human operators.
- Results from simulation and experiments with real robots are provided.

Mo1-3 11:20 - 11:40

**A Probabilistic Topological Approach to Feature Identification using a Stochastic Robotic Swarm**

Ragesh K. Ramachandran, Sean Wilson, Spring Berman
Arizona State University, U.S.A.

- Presents a novel automated approach to quantifying the topological features of an unknown domain using a swarm of robots with local sensing and limited or no GPS.
- A point cloud indicating the free space of the environment is extracted from a probabilistic map that is constructed using the robots' uncertain position data.
- Tools from topological data analysis, such as persistent homology, are applied to landmark points, which are computed from the point cloud, to construct barcode diagrams.
- The barcode diagrams reveal the numbers of different types of features in the domain.

Mo1-4 11:40 - 12:00

**From Ants to Birds: A Novel Bio-Inspired Approach to Online Area Coverage**

Luca Giuggioli\(^{\dagger}\), Idan Arye\(^{\ddagger}\), Alexandro Heiblum Robles\(^{\ast}\), Gal A. Kaminka\(^{\ddagger}\)

\(^{\dagger}\)Bristol Centre for Complexity Sciences, University of Bristol, UK
\(^{\ddagger}\)School of Biological Sciences, University of Bristol, UK
\(^{\ast}\)Computer Science Department, Bar Ilan University, Israel

- Development of a bio-inspired cognitive memory territorial algorithm for robotic swarm.
- Spatial exclusion is implemented through virtual barriers generated by recent robot collisions.
- Mean coverage time can be minimized with intermediate values of memory and movement persistence.
- The algorithm is written in Java within the MASON library to exploit excellent visualization packages.
Mo2-1 12:10 - 13:40

**Distributed Adaptive Locomotion Learning in ModRED Modular Self-Reconfigurable Robot**

Ayan Dutta, Prithviraj Dasgupta
Department of Computer Science, University of Nebraska at Omaha, USA
Carl Nelson
Department of Mechanical and Materials Engineering, University of Nebraska - Lincoln, USA

- We propose a stateless Q-learning based strategy for adaptive locomotion pattern generation for ModRED modular robot.
- Each module learns from its own past actions as well as from the relationship between its own actions and its neighboring modules’ actions.
- Our approach has also been shown to be adaptive to module failures.
- We have tested our proposed approach on ModRED and Yamar modular robots within Webots simulator.

Mo2-2 12:10 - 13:40

**Effects of Spatiality on Value-Sensitive Decisions Made by Robot Swarms**

Andreagiovanni Reina1, Thomas Bose1, Vito Trianni2 and James A.R. Marshall1
1University of Sheffield, UK
2ISTC, Italian National Research Council, Rome, Italy

- Value-sensitivity in decision-making
  - select the best option if its quality is above threshold
  - otherwise refrain from deciding until a sufficient-quality option becomes available
- Value-sensitivity is useful when options may be discovered at different times (e.g., because dispersed in space)
- We quantify the effects of spatiality in a value-sensitive decision problem
  - macroscopic models inspired by house-hunting honeybees
  - multagent implementation
  - swarm of 150 kilobot robots
- Results:
  - only qualitative match
  - quantitative agreement only at convergence
- Future work:
  - improve modelling techniques
  - implement agent strategies to reduce spatiality effects

Mo2-3 12:10 - 13:40

**Evo-bots: A Simple, Stochastic Approach to Self-Assembling Artificial Organisms**

Juan A. Escalera, Matthew J. Doyle, Roderich Groß
The University of Sheffield
Francesco Mondada
Ecole Polytechnique Fédérale de Lausanne

- Self-assembling modular robots with hybrid motion control, energy harvesting and sharing.
- Novel anchor mechanism used to enable stop-start motion. External fans induce modules to move semi-randomly.
- Energy harvesting, energy sharing, simple 2D-structure formation, motion control and light detection demonstrated experimentally.
- Long term goal is to create simple robotic ecosystem.

Mo2-4 12:10 - 13:40

**Evolving group transport strategies for e-puck robots: moving objects towards a target area**

Muhanad H. Mohammed Alkilabi1,2, Aparajit Narayan1, Chuan Lu1, Elio Tuci1
1Computer Science Department, Aberystwyth University, Aberystwyth, UK
2Computer Science Department, Kerbala University, Kerbala, Iraq

- A group of six robots is required to transport an elongated cuboid object 1 m from its initial position (Transports phase) and then to push it for another meter towards a nesting area (nesting phase).
- For this task, an optic-flow sensor has been appositely designed, built, and integrated into the e-puck structure.
- The best group transport strategy is fairly robust to deal with variability in object length and mass. It is also scalable to successfully operate with groups of different cardinality.
From Formalised State Machines to Implementations of Robotic Controllers

Wei Li, Alvaro Miyazawa, Pedro Ribeiro, Ana Cavalcanti, Jim Woodcock and Jon Timmis
University of York, UK
wei.li@york.ac.uk

• A state-machine based framework that supports both formal verification and automatic code generation for robotic controllers
• A rigorous connection between the specification of designed robotic controller and its implementation
• Controller can be specified either graphically or using a textual description
• Platform independent

Modelling Mood in Co-operative Emotional Agents

Joe Colenette, Katie Atkinson, Daan Bloembergen, Karl Tuyls
University of Liverpool, UK

• We are proposing a model of mood based on and validated through psychological research
• We use simulated mood and emotion to inform the decision making process
• We have shown that this model can be used to explore aspects of multi-agent systems.
• We have used this model to support cooperation in the iterated prisoner’s dilemma.

Multirobot Persistent Patrolling in Communication-Restricted Environments

Marta Romeo, Jacopo Banfi, Francesco Amigoni
Politecnico di Milano, Italy
Nicola Bastiolo
University of Milano, Italy

• A team of robots must persistently patrol a set of locations and report to a base station
• Only some locations of the environment allow the robots to communicate with the base station
• We introduce the persistent patrolling problem under this communication constraint
• We define some patrolling strategies suited for this framework
• Experimental evaluations show the effectiveness of the proposed approach in different settings

Network Characterization of Lattice-Based Modular Robots with Neighbor-to-Neighbor Communications

André Naz, Benoit Piranda, Thadeu Tucci, Julien Bourgeois
FEMTO-ST Institute, UMR CNRS 6174, Univ. Bourgogne Franche-Comte (UBFC), France
Seth Copen Goldstein
Carnegie Mellon University, USA

• We demonstrate that lattice-based modular robots with neighbor-to-neighbor communications form sparse and large-diameter networks.
• We provide tight bounds for the radius and the diameter of these systems.
• We highlight the fact that, because of the huge diameter and the huge average distance of massive-scale lattice-based networks, complex distributed algorithms for programmable matter may be challenging to design in an efficient way.

Optical Wireless Communications for Heterogeneous DARS

Patricio Cruz, Christoph Hintz, Jonathan West, and Rafael Fierro
MARHES Lab, University of New Mexico, USA

• Maintaining reliable communications on DARS is critically important for cooperative autonomy.
• Radio-frequency has some limitations that can be mitigated by complementing RF systems with optical wireless OW communications.
• Develop a model for a line-of-sight optical link between a quadrotor and a ground mobile vehicle.
• Define a connectivity cone over the receiver where a minimum transmission rate is guaranteed.
MONDAY, NOV 7 13:40 - 14:40
ORAL SESSION MO3

Session Chair: Michael Rubenstein (Northwestern University, USA)

Modular Robots and Smart Materials

Mo3-1 13:40 - 14:00

Geometrical Study of a Quasi-Spherical Module for Building Programmable Matter

Benoît Piranda, Julien Bourgeois
Univ. Bourgogne Franche-Comté (UBFC)
FEMTO-ST Institute, CNRS, France

• We propose a quasi-spherical 3D module geometry which answers to all constraints for building Programmable Matter:
  • Can be combined to regularly fill a 3D space (FCC lattice).
  • Have a large surface of contact (connectors), to latch neighbors, communicate and transfer power.
  • Can freely move from one position to another one by rolling over neighbors, using electro-static actuators.

Mo3-2 14:00 - 14:20

A Rule Synthesis Algorithm for Programmable Stochastic Self-Assembly of Robotic Modules

Bahar Haghighat and Alcherio Martinoli
Distributed Intelligent Systems and Algorithms Laboratory (DISAL), EPFL, Switzerland

• Design of a formal synthesis algorithm automatically deriving rulesets for highly concurrent self-assembly of robotic modules.
• The synthesized rulesets are directly applicable to robotic modules with no further tuning.
• Simulation results from microscopic (non-spatial) and submicroscopic (spatial) models of our robotic platform confirm higher performance of synthesized rulesets compared to related work in the literature.

Mo3-3 14:20 - 14:40

Distributed Camouflage for Swarm Robotics and Smart Materials

Yang Li, John Klingner, and Nikolaus Correll
University of Colorado, Boulder, USA

• We present a distributed algorithm for a swarm of active particles to camouflage in an environment.
• Each particle is equipped with sensing, computation and communication, allowing the system to take color and gradient information from the environment and self-organize into an appropriate pattern.
• The distributed camouflage algorithm can be broken into three phases: sensing color and recognize local pattern; reaching consensus on the global pattern; and reproducing the pattern.
Multi-Robot Estimation

Mo4-1 15:00 - 15:20

Distributed Laplacian Eigenvalue and Eigenvector Estimation in Multi-Robot Systems

Mehran Zareh, Lorenzo Sabattini, Cristian Secchi
University of Modena and Reggio Emilia, Italy

• This paper presents a novel methodology for estimating eigenvalues and eigenvectors of the Laplacian matrix, in multi-robot systems.
• The proposed algorithm is totally decentralized, since each robot needs only information from its neighbors.
• Eigenvalues and eigenvectors are simultaneously estimated.
• Simulation results show good convergence performances.

Mo4-2 15:20 - 15:40

Distributed Object Characterization with Local Sensing by a Multi-Robot System

Golnaz Habibi, Zachary Kingston, James McLurkin
Rice University, USA
Sándor Fekete
TU Braunschweig, Germany

• Two distributed algorithms are presented to estimate object dimensions and orientation.
• Distributed Principal Component Analysis (DPCA) is an approximation and sensitive to robots distribution, but easy to implement and more robust to sensor errors.
• Distributed Rotating Calipers (DRC) algorithm computes exact geometry, but it is sensitive to sensor measurement error.
• Our main objective is to use object characterization to generate a safe path and navigate an object in a collective transport.

Mo4-3 15:40 - 16:00

Construction of Optimal Control Graphs in Multi-Robot Systems

Gal A Kaminka, Ilan Lupu and Noa Agmon
Bar-Ilan University, Israel

• Goal: Construct optimal control graphs
• Used for formation maintenance, finding shared coordinate system
• Built from monitoring multigraph: graph representing all possible sensing of the teammates
• Can represent monitoring cost, accuracy
• Need to choose local anchor (whom to sense), and global anchor (whom will lead)
• Optimality criteria:
  • Minimize total cost
  • Minimize accumulated cost to global anchor
• Experimental results: choosing optimal global and local anchor improves accuracy
  • Examined in simulation and real Hamster robots
Multi-Robot Systems in Applications I

Mo5-1 16:20 - 16:40
Formation Control of a Drifting Group of Marine Robotic Vehicles
Nicholas R. Rypkema, Henrik Schmidt
MIT, USA

- Motivation: Multiple AUVs/ASVs in formation as a configurable receiver array for acoustic measurements or for oceanographic sampling, while leveraging ocean currents for propulsion of the group as a whole.
- Three distributed, low-communication formation control algorithms compared in simulation with 20 AUVs and realistic currents.
- Field experiments with three ASVs performed in a river environment to validate behavior of the most promising algorithm.

Mo5-2 16:40 - 17:00
Decision-Making Accuracy for Sensor Networks with Inhomogeneous Poisson Observations
Chetan D. Pahlajani
Indian Institute of Technology, Gandhinagar, India
Indrajeeet Yadav, Herbert G. Tanner, Ioannis Poulakakis
University of Delaware, USA

- Network of sensors observes a time-inhomogeneous Poisson process
- Sensors communicate according to certain network topologies
- An index captures the effect of centrality in the network and proximity to the signal source: quantity vs. quality of information
- Application to detecting nuclear material in transit in urban environments

Mo5-3 17:00 - 17:20
Multi-Swarm Infrastructure for Swarm Versus Swarm Experimentation
Duane Davis1, Timothy Chung2, Michael Clement1, Michael Day3
1Naval Postgraduate School, Monterey, CA
2Defense Advanced Research Projects Agency, Arlington, VA
3Georgia Tech Research Institute, Atlanta, GA

- Aerial swarm competition modeled on a capture-the-flag event.
- Software Arbiter (referee) for competitive swarm versus swarm events.
  - Virtual sensor for both swarms.
  - Enforcement of competition rules.
  - Evaluation of offensive and defensive events.
- Demonstrated utility in assessment of competitive swarm behaviors.
- Supports simulated or live-fly experiments
TUESDAY, NOVEMBER 8
TECHNICAL PROGRAM DIGESTS
Multi-Robot Planning

Tu1-1 10:20 - 10:40

Multi-Robot Informative and Adaptive Planning for Persistent Environmental Monitoring

Kai-Chieh Ma, Zhibei Ma, Lantao Liu, Gaurav S. Sukhatme
University of Southern California, USA

- Gaussian Processes are used to build an environmental model, based on which persistent monitoring tasks are performed.
- Potential future observation points that minimize model prediction uncertainty are generated.
- Observation points are used as waypoints and routed by a matching-graph based multi-robot path planning method.
- The resulting paths are conflict-free, informative, and adaptive to the environmental dynamics.

Tu1-2 10:40 - 11:00

Decomposition of Finite LTL Specifications for Efficient Multi-Agent Planning

Philipp Schillinger1,2, Mathias Bürger1
1 Robert Bosch GmbH, Corporate Research, Germany
2 KTH Royal Institute of Technology, Sweden

- Finite LTL specifications can be decomposed into independent parts
- Decomposition significantly reduces state space complexity for multi-agent planning
- Automaton-based approach to determine possible choices for decomposition
- Determination of decomposition choices independent of team size or environment
- Evaluated ROS implementation of the presented approach

Tu1-3 11:00 - 11:20

United We Move: Decentralized Segregated Robotic Swarm Navigation

Fabrício R. Inácio, Douglas G. Macharet, Luiz Chaimowicz
Universidade Federal de Minas Gerais, Brazil

- Navigation maintaining groups segregated can be an important task within swarms.
- We propose the use of ORCA and Flocking Behaviors to navigate a swarm of robots in a segregative manner.
- Simulations and real experiments show the efficiency and feasibility of the proposed approach.

Tu1-4 11:20 - 11:40

Informative Path Planning and Mapping with Multiple UAVs in Wind Fields

Doo-Hyun Cho, Jung-Su Ha, and Han-Lim Choi
KAIST, Republic of Korea

- Systematic procedure for informative path planning and environmental mapping
  - Maximization of mutual information using multiple UAVs
  - Calculation of UAV moving cost in wind field dynamics with FMT* algorithm
  - Path generation for each UAV with MIMMDTSP formulation
  - Map of the information for the region of interest is estimated with Gaussian process regression
  - Simulation with realistic wind field and RF signal data
A Decentralized Control Strategy for Resilient Connectivity Maintenance in Multi-Robot

Cinara Ghedini and Carlos Ribeiro
Lorenzo Sabatini
University of Modena and Reggio-Emilia, Italy

- Multi-robot network elements are subject to unexpected failures, which can lead networks to fragmentation, resulting in inoperative or reduced services.
- Connectivity maintenance mechanisms, per se, do not guarantee robustness to failures w.r.t connectivity.
- A mechanism, based on local information, for assessing and mitigating vulnerable topological configuration is proposed.
- The mechanism is validated combined with a connectivity maintenance and a collision avoidance control laws.

Bundling policies for sequential stochastic tasks in multi-robot systems

Changjoo Nam
Robotics Institute, Carnegie Mellon University, USA
Dylan A. Shell
Department of Computer Science & Engineering, Texas A&M University, USA

- Synergistic tasks have the property that the cost per task decreases as more are bundled together.
- Suppose such tasks arrive sequentially and indefinitely.
- How many tasks should be bundled together?
- We conduct a domain-independent analysis of task bundle size with respect to the system cost and the timespan of tasks.
- We introduce and study bundling policies.

Human Responses to Stimuli Produced by Robot Swarms - The Effect of the Reality Gap on Psychological state

Gaëtan Podevijn, Rehan O’Grady, Carole Fantini-Hauwel, Marco Dorigo
IRIDIA, ULB, Belgium
Faculty of Psychology, ULB, Belgium

- The reality-gap is the inherent discrepancy between reality and simulation.
- We hypothesized that stimuli produced by a real robot swarm or by a swarm simulated on a computer screen induce different reactions in human operators.
- We show that human operators have stronger physiological responses, workload and reaction time when observing real swarms.
- We propose virtual reality as an alternative to computer screen-based simulations and we show that its use helps mitigate the reality-gap.

HyMod: A 3-DOF Hybrid Mobile and Self-Reconfigurable Modular Robot and its Extensions

Christopher Parrott, Tony J. Dodd, Roderich Groß
The University of Sheffield, United Kingdom

- A hybrid between the chain, lattice, and mobile self-reconfigurable modular robot types.
- Features a 3-DOF spherical joint and four high-speed genderless (HiGen) connectors.
- Able to rotate freely in place within a cubic lattice position and independently drive around an environment via differential wheels.
- An analysis of the module’s geometry and reconfigurability is presented, and details of its mechanics and electronics discussed.
- Four extension modules are introduced to augment the capabilities of HyMod.
OuijaBots: Omnidirectional Robots for Cooperative Object Transport with Rotation Control using No Communication

• Force and torque coordination without communication by sensing the motion of the object.
• A leader robot guides the team and steers both the translation and orientation of the object.
• Follower robots are proven to contribute positive forces and torques.
• Verified in experiments using 4 custom designed omnidirectional robots called OuijaBot with force/torque/velocity sensing capabilities.

Four omnidirectional robots transporting a pallet together.

The Effectiveness Index Intrinsic Reward for Coordinating Service Robots

• Use reinforcement learning to select between different coordination methods for collision avoidance.
• Use an intrinsic reward function: Effectiveness Index
• Use Hierarchical learning to learn method and its parameters in parallel
• Applied in Kiva Systems (Amazon Robotics) Order Picking simulator

Results:
• Hierarchical learning highly effective
• Significantly improves on the original non-learning methods default in the simulator

Triangular Networks for Resilient Formations

We propose a formation topology that is resilient to one malicious node in the consensus update process. It satisfies two important properties for distributed systems:
• It can be constructed incrementally.
• Its robustness can be verified through a distributed method by using only neighborhood-based information.
We show that triangular robust networks guarantee asymptotic consensus in the face of a malicious agent.

Vertex: A New Distributed Underwater Robotic Platform for Environmental Monitoring

• A novel underwater robot designed for cooperative operation in scientifically relevant deployments
• Environmental sensor payload with up to 7 different sensors
• Acoustic ranging system for underwater relative positioning between robots
• Low frequency radio for scalable underwater communication
• A powerful HIL simulation framework
• Data presented from multiple outdoor field campaigns with a single robot

Vertex AUV in Lake Geneva
**TUESDAY, NOV 8 14:40 - 16:00**

**ORAL SESSION TU3**

Session Chair: Marco Dorigo (Université Libre de Bruxelles, Belgium)

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**Swarm Robotics I**

**Tu3-1 14:40 - 15:00**

**Discovery and Exploration of Novel Swarm Behaviors given Limited Robot Capabilities**

Daniel S. Brown  
University of Texas at Austin, USA  
Ryan Turner, Oliver Hennigh, Steven Loscalzo  
Air Force Research Laboratory, USA

- **Research Question:** What emergent behaviors are possible in a swarm of robots possessing specific capabilities?
- **Method:**
  - Use evolutionary-based novelty search to explore behavior space.
  - Cluster behaviors in feature space to identify behavior types.
- **Results:** Found six possible behaviors for a simple binary-sensor robot model.

![Discovered Behaviors](image_url)

**Tu3-2 15:00 - 15:20**

**Towards Differentially Private Aggregation of Heterogeneous Robots**

Amanda Prorok, Vijay Kumar  
GRASP Lab.  
University of Pennsylvania, USA

- **Motive:** Conceal individual robot roles in heterogeneous system, with the ultimate goal to secure resilience.
- **Use differential privacy theory to propose closed-form expression of leakage of system.**
- **Use of our model enables analysis of privacy as a function of system dynamics (topology, rates, composition).**
- **We propose design rules for private aggregation: (i) balance topology, and (ii) throttle output of aggregates.**

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**Tu3-3 15:20 - 15:40**

**Emergence and inhibition of synchronization in robot swarms**

Fernando Perez-Diaz, Stefan M. Tenkenwalder, Ruediger Zillmer, Roderich Gross  
The University of Sheffield, UK

- We study firefly synchronization in swarms of mobile robots interacting with each other via pulses of light that are detected with onboard cameras.
- We find in simulation that the synchronization time exhibit three non-trivial dynamical regimes depending on the speed of the robots and the size of the camera’s field of view.
- We validate the above results in a swarm of real e-puck robots.

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**Tu3-4 15:40 - 16:00**

**Programmable Self-Disassembly for Shape Formation in Large-Scale Robot Collectives**

Melvin Gauci, Radhika Nagpal  
Harvard University, USA  
Michael Rubenstein  
Northwestern University, USA

- We present a subtractive method for a large-scale robot collective to autonomously form a wide range of user-specified shapes and validate this method on 725 Kilobots.
- The subtractive approach has several advantages over additive approaches; it is more tolerant to noisy robot motion, and consequently much faster.
- Our results suggest that a self-disassembly algorithm can achieve a wide class of shapes with high efficiency and accuracy, making it a good candidate for shape formation in modular robots and programmable materials.
Multi-Robot Systems in Applications II

Tu4-1 16:20 - 16:40

Robust Coordinated Aerial Deployments for Theatrical Applications Given Online User Interaction via Behavior Composition
Ellen A. Cappo, Arjav Desai, Nathan Michael
Carnegie Mellon University, USA

- We enable unscripted human-robot theatrical performances by translating performer intent online into dynamically feasible trajectories for multiple aerial robots.
- Users input intent as behavior commands composed of motion descriptors, that are used to design multi-robot formation trajectories. The system validates behavior transitions through offline dynamic simulation and verifies and refines trajectories online to meet collision and actuator constraints.
- We evaluate the system through dynamic simulation and performance of a three act theatrical work spanning fifteen minutes of coordinated flight by a six robot team.

Tu4-2 16:40 - 17:00

Distributed Convolutional Neural Networks for Human Activity Recognition in Wearable Robotics
Dana Hughes, Nikolaus Correll
University of Colorado Boulder, United States

- On-body sensors provide a wearable solution to human activity recognition.
- Convolutional Neural Networks (CNN) generate accurately classify activities when using a large number of sensors.
- Monolithic CNN require large computing resources (memory, computing time, etc.)
- CNNs are distributed on multiple hardware nodes located at body and limbs.
- Similar accuracy achieved with distributed CNNs while requiring less computing resources per node, and modest communication requirements.

Tu4-3 17:00 - 17:20

Construction Planning for a Modularized Rail Structure
Rui Fukui, Yuta Kato, Gen Kanayama, Ryo Takahashi, Masayuki Nakao,
The University of Tokyo, JAPAN

- We propose an automated construction system of a modularized rail structure for working robots to have access to any operational point in hazardous environments such as nuclear accident sites.
- To realize time-efficient and economical construction of the structure, it is necessary to integrate three planning procedures.
- A simulation experiment demonstrates that the geometrical constraint conditions of the structure can reduce the search space of selecting module types.
**Multi-Robot Control**

**We1-1 10:20 - 10:40**

**Persistent Multi-Robot Formations with Redundancy**

Alyxander Burns  
Mount Holyoke College, USA

Bernd Schulze  
University of Lancaster, UK

Audrey St. John  
Mount Holyoke College, USA

- Persistent formations are composed of leader and follower autonomous agents.
- Leader controls movement of entire formation.
- Followers sense and maintain local distances to other robots so that global formation is preserved.
- Algorithms construct persistent leader-follower formations with redundancy.
- Redundancy model permits sensing failures.
- Simulation results confirm expected behavior.

**We1-2 10:40 - 11:00**

**Chase Your Farthest Neighbour**

A simple gathering algorithm for simple agents

Rotem Manor and Alfred M. Bruckstein  
Technion, Haifa, Israel

- A group of oblivious, identical and indistinguishable mobile robotic agents with limited visibility sensors and low computational capabilities.
- Such robots, implementing a “Chase the farthest neighbour” policy, perform the task of gathering to a point within a finite time or a finite expected number of time steps.
- We prove it using results from basic geometry and from the theory of random-processes.

**We1-3 11:00 - 11:20**

**A Comparative Study of Collision Avoidance Algorithms for Unmanned Aerial Vehicles: Performance and Robustness to Noise**

Steven Roelofsen, Alcherio Martinoli  
Distributed Intelligent Systems and Algorithms Laboratory, EPFL, Switzerland

Denis Gillet  
Coordination and Interaction System Group, EPFL, Switzerland

- We compare the robustness to noisy sensing of two collision avoidance algorithms.
- One algorithm is based on potential fields and the other is based on velocity obstacles.
- Results using high-fidelity simulation and real robots are presented.
- We found that the algorithm based on velocity obstacle is more efficient (less deviation from desired trajectories) but less robust to noisy sensing.
**Swarm Robotics II**

**We2-1 11:40 - 12:00**

**Decentralized Progressive Shape Formation with Robot Swarms**
Carlo Pinciroli
Worcester Polytechnic Institute, USA
Andrea Gasparri
Università Roma Tre, Italy
Emanuele Garone
Université Libre de Bruxelles, Belgium
Giovanni Beltrame
Polytechnique Montreál, Canada

**PROBLEM**
- Achieving any given shape defined as a point cloud in a distributed manner with a swarm of robots

**CONTRIBUTION**
- An algorithm that transforms a point cloud into a directed acyclic graph (DAG)
- A motion control law that, from the DAG, allows a swarm to achieve the target shape in a decentralized manner
- A theoretical model, which provides sufficient conditions on the convergence of the control law

**We2-2 12:00 - 12:20**

**Evolving behaviour trees for swarm robotics**
Simon Jones, Matthew Studley, Sabine Hauert, Alan Winfield
Bristol Robotics Laboratory, UK

- Evolved swarm controllers are often difficult to understand
- Behaviour trees are a hierarchical, modular, comprehensible controller architecture, used in computer game AI
- We evolve behaviour trees using Genetic Programming for a kilobot swarm foraging task
- We show it is possible to analyse the best evolved tree to understand how it works

**We2-3 12:20 - 12:40**

**Localization of inexpensive robots with low-bandwidth sensors**
Shiling Wang, Francis Colas, Ming Liu, Francesco Mondada, Stéphane Magnenat
ETH Zurich, Switzerland – Inria, France – City University HK, Hong Kong – EPFL, Switzerland – EPFL, Switzerland

- Low-cost mobile robots currently cannot localize without external electronics.
- We propose a solution using dead reckoning and infrared sensors measuring the color of the ground.
- Our approach builds on a recursive Bayesian filter.
- We show accurate localization on many patterns.
- We give a theoretical estimate and a validation of the necessary traveled distance for convergence.
- We demonstrate real-time localization with Thymio.
- Our results provide a solid base on which to build navigation or behavioural algorithms.
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