Networked Robots

By Volkan Isler, Brian Sadler, Libor Přeučhil, and Shuichi Nishio

Many robotics applications require robots to communicate with each other, with a human operator, or with a remote server. The IEEE Robotics and Automation Society's Technical Committee (TC) on Networked Robots focuses on research issues related to robots connected to a communication network. The TC was founded in 2001. The name "Networked Robots" was adopted in 2004. The original focus of the TC was on Internet-based teleoperated robots. At the moment, most of the research activity in our TC revolves around robotic networks and cloud robotics.

Research Activities

Robotic Networks

In multirobot systems, robots must coordinate their actions either by communicating with each other or with a central server. Research topics include the development of algorithms and systems for connectivity maintenance, data gathering, robotic routers, network deployment, repair and maintenance, and teleoperation. Figures 1–8 show examples of ongoing research topics in this area.

Cloud Robotics

As cloud computing is changing the computing landscape, the benefits of connecting robots to the cloud is becoming evident. According to Ken Goldberg, there are at least four potential advantages to connecting robots to the cloud:

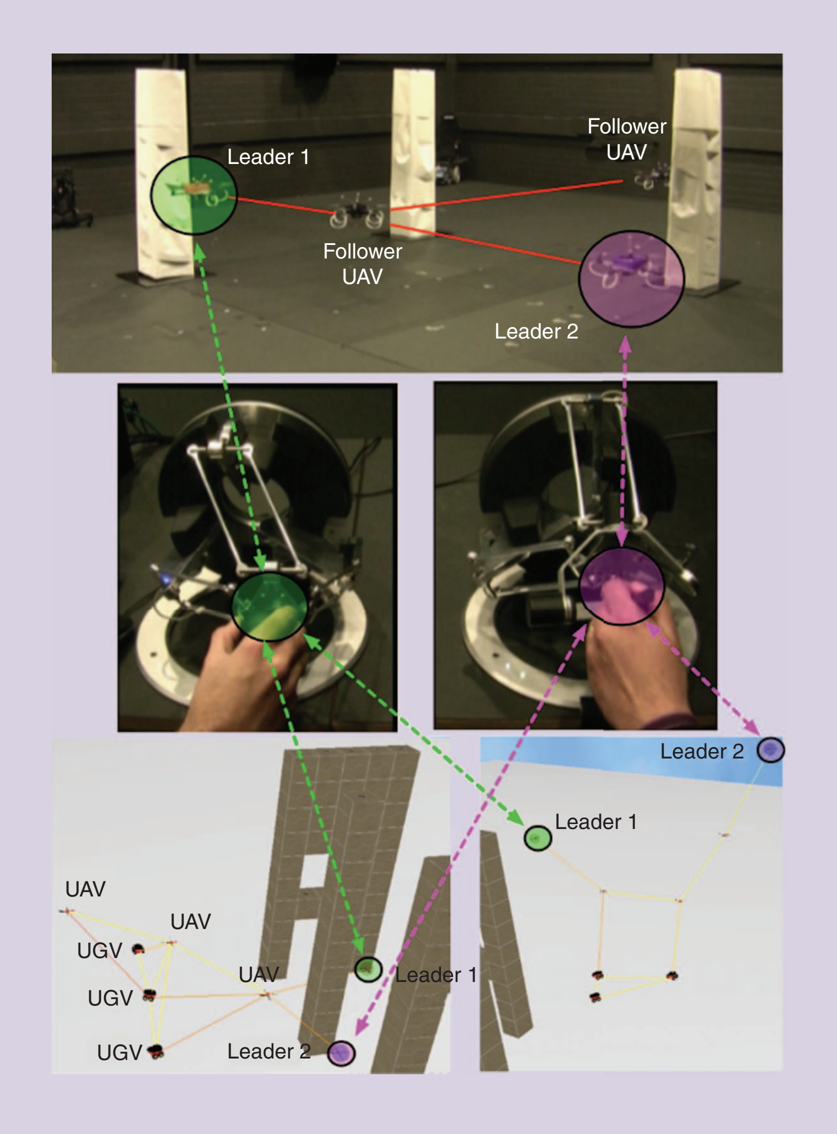

Figure 1. Robuffo Giordano et al. [8] studied how a group of quadrotor unmanned aerial vehicles (UAVs) can preserve group connectivity in a flexible and decentralized way while navigating in a cluttered environment. In particular, gain/loss of pairwise links (due to sensing/communication constraints) is allowed as long as the interaction graph remains connected. A shared control architecture is also built on top of this "connectivity maintenance" framework, allowing one or more human operators to easily steer the gross motion of the robot group. UGV: unmanned ground vehicle. (Photo courtesy of Dr. Paolo Robuffo Giordano and Dr. Antonio Franchi.)

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Figure 2. The Advanced Robotic Systems Engineering Laboratory (ARSENL) team from the Naval Postgraduate School was able to successfully launch, fly, and land 20 UAVs autonomously at Camp Roberts, California, on 15 May 2015, which it deployed in two subswarms (ten UAVs each) and operated using the ARSENL-developed swarm operator interfaces. The UAVs were able to perform basic leader-following cooperative behaviors, exchanging information among themselves via wireless links. This is a first-of-its-kind demonstration of this magnitude for large-scale, autonomous fixed-wing UAV teams [6]. (Photo courtesy of ARSENL.)

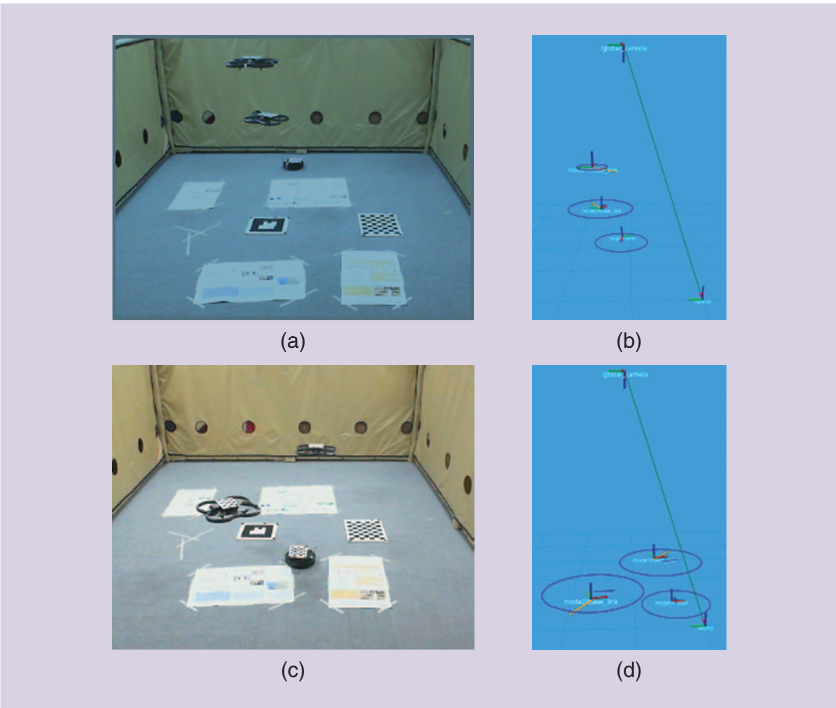

Figure 3. Researchers at the University of Southern California considered the cooperative control of a team of robots to estimate the position of a moving target using onboard sensing. The robots were required to estimate their positions using relative onboard sensing while concurrently tracking the target. They developed a probabilistic localization and control method, taking into account the motion and sensing capabilities of the individual robots to minimize the expected future uncertainty of the target position. A highlight of the approach is that it reasons about multiple possible sensing topologies and incorporates an efficient topology switching technique to generate locally optimal controls in polynomial time complexity [5]. (Photos courtesy of University of Southern California Robotics Embedded Systems Laboratory and Automatic Coordination of Teams Laboratory.)

- *big data*—access to updated libraries of images, maps, and object/product data
- *cloud computing*—access to parallel grid computing on demand for statistical analysis, learning, and motion planning
- *collective learning*—robots and systems sharing trajectories, control policies, and outcomes
- *human computation*—use of crowdsourcing to tap human skills for analyzing images and video, classification, learning, and error recovery.

The cloud can also provide access to 1) data sets, publications, models, benchmarks, and simulation tools; 2) open competitions for designs and systems; and 3) open-source software. Cloud robotics and automation raise critical new questions related to network latency, quality of service, privacy, and security. Extending earlier work that links robots to the Internet, cloud robotics and automation build on emerging research in the cloud computing, machine learning, big data, open-source software, and major industry initiatives such as the Internet of Things, smarter planet, industrial Internet, and industry 4.0.

Some of our members' activities related to cloud robotics are shown in Figures 9–11.

Other TC Activities

The TC maintains a research blog (networked-robots.cs.umn.edu), a LinkedIn group, and a mailing list. TC members were actively involved in the organization of a number of high-profile workshops. These included

- the National Science Foundation/Army Research Laboratory (NSF/ARL) Workshop on Cloud Robotics and Real-Time Big Data (http://cloud-robotics.cs.umn.edu)
- the Workshop on the Algorithmic Foundations on Robotics (WAFR) 2014, which featured many networked robots papers and plenaries by Oussama Khatib, Vijay Kumar, and Cagatay Basdogan focusing on various networking and communications aspects of robotics
- the Networked Robots Workshop at the 2015 European Robotics Forum
- numerous workshops at the IEEE International Conference on Robotics and

Automation and the IEEE/Robotics Society of Japan International Conference on Intelligent Robots and Systems.

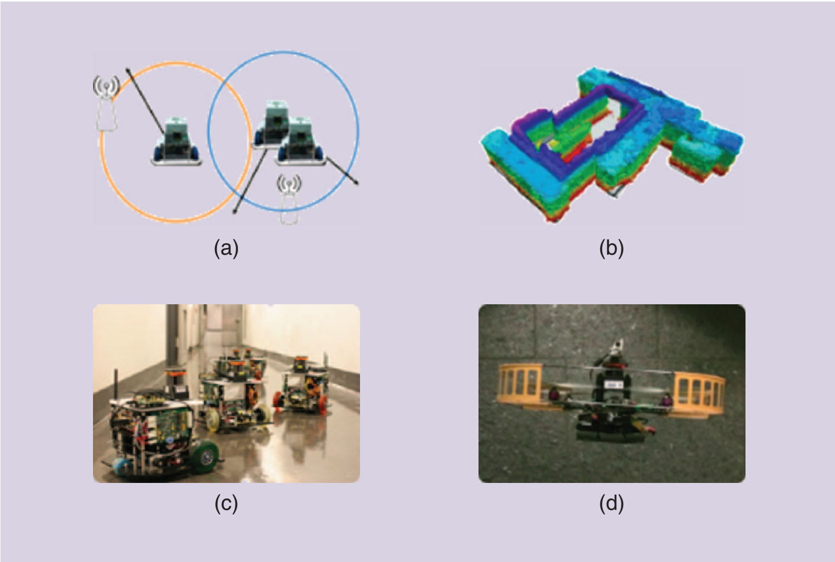

Figure 4. Researchers at the GRASP Laboratory at the University of Pennsylvania are developing swarms that can autonomously navigate and explore unknown and potentially hostile environments, without a designated leader, with limited communications between its members, and/or with different and potentially dynamically changing roles for its members. [Photos courtesy of Ben Charrow (student), Nathan Michael (coadvisor), and Vijay Kumar (coadvisor). See http://kumar.grasp.upenn.edu.]

Conclusion

Research in networked robotics continues to be extremely active. Our TC has been dynamically adjusting its focus to support and promote research in the area. Furthermore, networking plays a crucial role in multirobot systems, agricultural and marine robotics, and smart environments. Our members closely collaborate with associated technical committees in these areas. As the roles of big data, communication, and coordination become more prominent in robotics, we expect networking to maintain a crucial role.

Acknowledgments

Special thanks to Ken Goldberg for providing most of the text on cloud computing. Volkan Isler also thanks

Figure 5. In a networked system, there are a few key issues that need to be considered for data sharing and processing. These issues are phrased in the form of the following four questions. First, what type of data is shared among robots? Second, how are these data shared among robots? Third, where are these data processed? Finally, how is the processing performed? Howard Li and his group investigated these issues of data communication, data sharing, data distribution, and data processing [3].

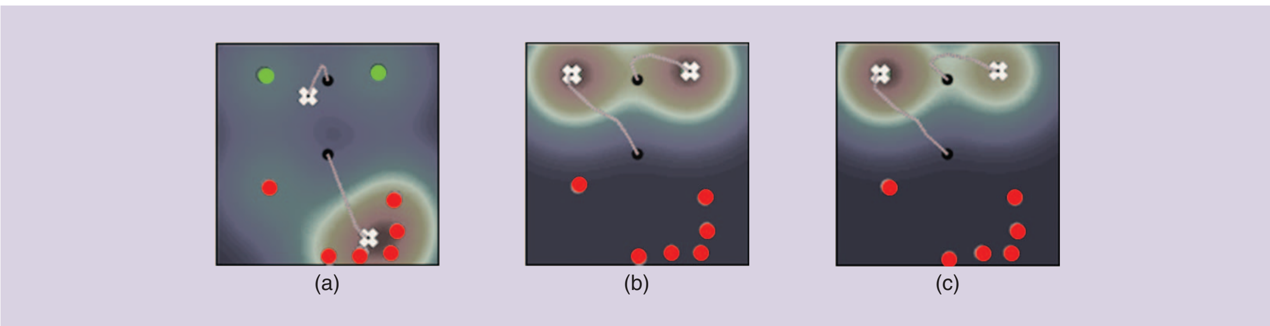

Figure 6. The promise of multirobot networks centers on the assumption that communication among robots is accurate and trustworthy. Even a simple-to-execute cyberattack, where, through spawning false identities, a single malicious robot gains disproportionate influence in the network, can be crippling to the entire system. Researchers at MIT's CSAIL Lab have developed a new and effective method of defense against these cyberattacks that fingerprints all transmitted wireless signals so that malicious robots can be automatically detected and quarantined, with no extra hardware or complex cryptographic schemes necessary. The figure shows their solution applied to a coverage problem where two quadrotor robots (shown as white Xs) must provide coverage to legitimate clients (green dots) in the presence of many falsely created clients (red dots) [7]. (a) No security, (b) Oracle, and (c) our system. (Photo courtesy of Daniela Rus.)

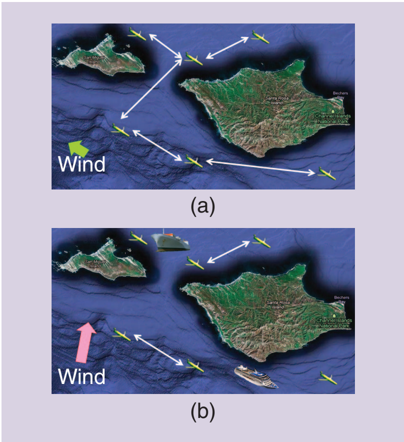

Figure 7. Underwater multirobot planning requires fully distributed algorithms capable of operating at any level of communication. Calm wind and low shipping activity results in (a) a connected network of underwater vehicles, but high wind and high shipping activity disconnects the same network of vehicles, as shown in (b) [2]. (Photos courtesy of G. Hollinger et al. and University of Southern California Robotic Embedded Systems Laboratory.)

Figure 8. Researchers at the Robotic Sensor Network Laboratory at the University of Minnesota have built a network of autonomous surface vehicles that can collaboratively find and track radio-tagged invasive fish. The tracking algorithm presented by [4] can break and reestablish communication while achieving desired levels of tracking performance. (Photo courtesy of RSN Lab, University of Minnesota.)

Daniela Rus, Paolo Giordano, Antonio Franchi, Joo-Ho Lee, Howard Li, Geoff Hollinger, Gaurav Sukhatme, Tim Chung, and Vijay Kumar for providing research highlights.

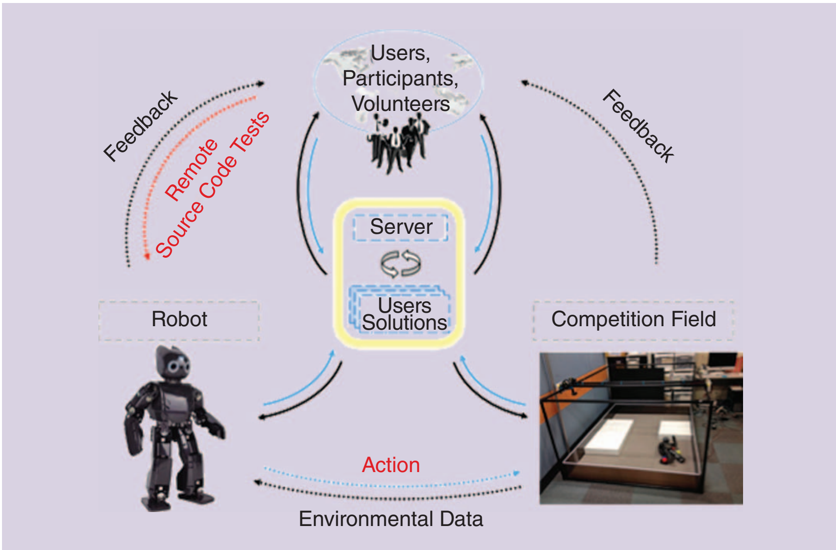

Figure 9. In their project League of Everybody, Joo-Ho Lee and his group are building a cooperative–competitive robot development environment through the Internet [1].

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Figure 10. The April 2015 issue of *IEEE Transactions on Automation Science and Engineering* includes a special section with 11 papers on the emerging area of cloud robotics and automation describing system architectures and applications to navigation, disaster-response, grasping, and assembly. (Photos courtesy of Ken Goldberg.)

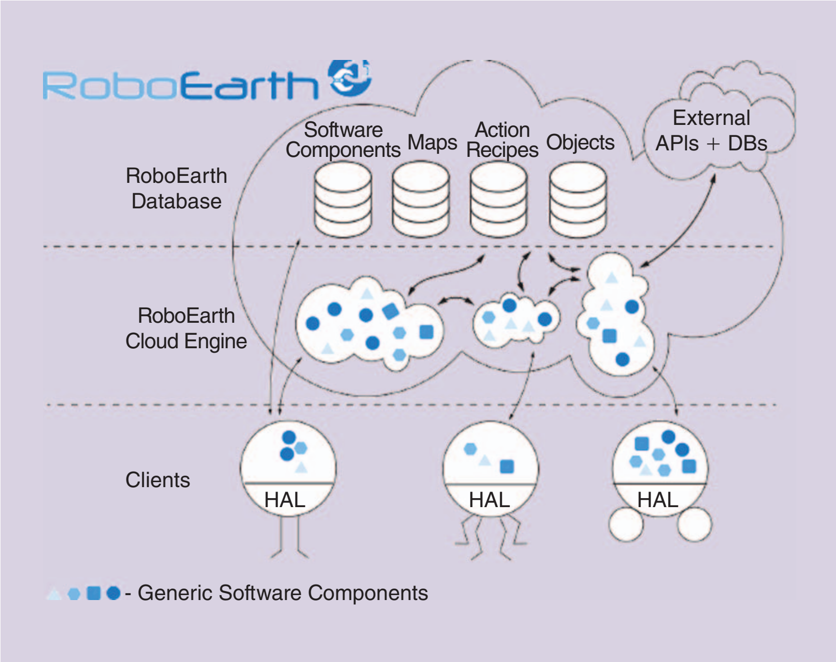

Figure 11. The goal of the RoboEarth project was to offer a cloud robotics infrastructure, which includes everything needed to close the loop from robot to the cloud and back to the robot. RoboEarth's World-Wide-Web style database stores knowledge generated by humans—and robots—in a machine-readable format. APIs: application program interfaces; HAL: hardware abstraction layer. (Photo courtesy of http://roboearth.org.)

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Biorobotics with Hybrid and Multimodal Locomotion

By Kin Huat Low, Samer Mohammed, Tianjiang Hu, Justin Seipel, Ravi Vaidyanathan, and Jorge Solis

The IEEE Robotics and Automation Society (RAS) Technical Committee (TC) on Biorobotics was formed with the goal of providing a forum and dissemination mechanism for the interaction between biological and artificial (autonomous or semiautonomous) systems and to present biology as a learning tool for novel engineering paradigms. In 2007, in an effort to define the scope of the technical field of the TC, the TC on Biorobotics was created to focus on various research fields that involve the understanding and implementation of complex living organisms by virtue of mechatronic systems. One such field is biologically inspired robotics, which is characterized by a multidisciplinary approach that aims to strengthen the collaboration between roboticists and biologists. To this end, two main approaches are adopted for research in Biorobotics: 1) the application of biological concepts/methodologies to improve the current capabilities of robots, for example, extending the robot's flexibility and robustness by adopting design principles of biological systems and 2) the application of advanced robotic technology to improve the current techniques/methodologies adopted by biologists. The principles and techniques of hybrid and multimodal locomotion recently have been emphasized and explored by researchers for better performance of bioinspired movements.

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Highlights of Recent Activities

TC-Organized Workshop at IROS 2013

The IEEE RAS TC on Biorobotics organized the workshop "Biologically Inspired Based Strategies for Hybrid and Multimodal Locomotion" in conjunction with the IEEE International Conference on Intelligent Robots and Systems (IROS), held at Tokyo Big Sight, Japan, on 3–7 November 2013 (Figures 1 and 2).

Biologically based concepts for hybrid and multimodal locomotion have revealed new challenges regarding mechanical design, sensor integration,