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FEATURES

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ON THE COVER

The cover shows the *IEEE Spectrum* iPad app, which has the goal of bringing the world of the robotics to a broad audience, from the young people who are interested in the field to the researchers who want to learn more about the robot projects around the world. See page 98 for details.

IMAGE: © BRIDGET COLLINS

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COLUMNS & DEPARTMENTS

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FROM THE EDITOR'S DESK

Open Access

By Peter Corke

Welcome to the December issue. This is our annual nonspecial issue, a place where we get a chance to publish articles on a diverse range of topics that reflect the exciting breadth of activities within our community. In addition to the technical articles and our usual columns, we have the second article from IEEE Robotics and Automation Society's robotics history project. This piece is about John McCarthy, the founder of the Stanford AI Laboratory, who died last year. According to Ruzena Bajcsy, one of McCarthy's many students, "John was a mathematician but also a visionary. He considered robotic research an essential part of the artificial intelligence field. He recognized the value of real physical system for validation of AI theories."

The Society is now deploying iThenticate on its transactions and the magazine.

I have mentioned open access a few times as well as the IEEE's response to this important movement in technical publishing. Proposals have firmed up around what is being called the hybrid journal open-access model, which means that open-access and traditional papers are published together in the same journal and on IEEE *Xplore*. The author chooses whether or not the paper is open access; the publishing fee for an open access paper has been set at US$1,750. Open-access papers will be suitably identified on IEEE *Xplore* and, of course, can be downloaded for free. Early open-access discussions only covered transactions, but magazines can now opt in. Happily, our Society has decided in favor of the magazine adopting the hybrid model. This means that open-access articles may now be published in the Magazine. Please see the announcement on page 21, for more information. The magazine's manuscript submission process is being revised to reflect this option. Please note that our sister publications, *IEEE Transactions on Robotics (T-RO)* and *IEEE Transactions on Automation Science and Engineering (T-ASE)* also support the hybrid journal open-access model.

Another IEEE-level innovation, decided by the Board of Directors in July, is the creation of what is being called the megajournal. This is a rapid-publication, open-access, electronic-only publication spanning all IEEE fields of interest. Benefits of the megajournal to authors include rapid publication and application focus.

The problem of plagiarism is steadily growing, as discussed in the article on page 85. Our Society recently tried the iThenticate software and, unfortunately, found a disturbing number of positives. The Society is now deploying iThenticate on its transactions and the magazine; the software will routinely scan all submitted manuscripts and provide a similarity report to the editors-in-chief.

Our front cover shows the iPad app developed by *IEEE Spectrum* and features many robots created by our members. It is a great way to show both the achievements and diversity of our field. More details are on page 98.

Enjoy the issue, have a happy new year, and we will be back in 2013.

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Growing Membership in IEEE RAS

By David E. Orin

The Eighth IEEE International Conference on Automation Science and Engineering (CASE) was held in Seoul, Korea 20–24 August, 2012. As our flagship conference in the automation area, it was good to hold the conference in the Asia and Pacific region of the IEEE (Region 10), where automation is having an increasing impact on industry. It was my first opportunity to attend CASE, and I am shown in Figure 1 with General Chair Hyouk Ryeol Choi, Sungkyunkwan University, Korea. Nak Young Chong, JAIST, Japan, was the program chair for the conference. I would like to express my appreciation to Prof. Choi and Prof. Chong as well as the organizing team for an excellent conference that resulted in a record number of attendees (more than 250). See conference report on page 96.

Figure 1. President David Orin (left) with General Chair Hyouk Ryeol Choi at the welcome reception of CASE 2012, Seoul, Korea.

Record Membership

The IEEE Robotics and Automation Society (RAS) passed a milestone in July 2012 when its membership topped 10,000 for the first time, with 10,023 members. Figure 2 shows our total membership over our almost 25-year history, along with the breakdown of the Society's higher-grade members, student members, and affiliates. (Affiliates are members of RAS but not members of the IEEE and have reduced IEEE benefits and fees.) Note that our membership growth has been relatively flat, generally between 6,000 and 7,000 for most of our history, surpassing 7,000 only recently in 2009. Since then, we have experienced double-digit growth by percentage; for the five-year period through 2011, we had an approximate growth of 50%.

Among the 38 IEEE technical Societies, ours is the only one that has consistently experienced double-digit, year-over-year growth in the past year. We are now the seventh largest Society in the IEEE (the IEEE Computer Society and IEEE Communications Society are the largest technical societies) and the largest Society in IEEE Technical Division X, which includes the Control Systems Society and the Engineering in Medicine and Biology Society.

Membership Growth in the IEEE Regions

In recent years, IEEE membership growth has been stronger outside the United States (Regions 1–6) and Canada (Region 7), especially in Region 9 (Latin America) and Region 10 (Asia and Pacific). This is also true for RAS, although we have had strong growth in all regions. Figure 3 shows the composition of RAS by region at the end of 2007 and at the end of 2011. While the

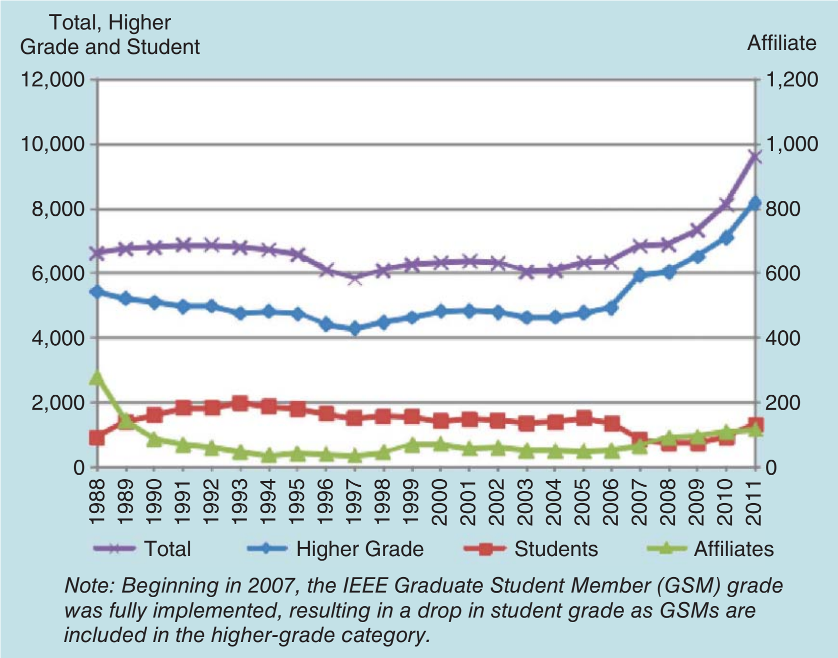

Figure 2. RAS membership statistics over its almost 25-year history.

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Data		H42-20-S300-R		H54-100-S500-R		H54-200-S500-R	
		Unit	Data	Unit	Data	Unit	Data
Rated voltage		V	24	V	24	V	24
No load speed		RPM	28.3	RPM	35.2	RPM	35
No load current		A	0.61	A	1.06	A	1.18
Continuous operation	Speed	RPM	15.59	RPM	32.7	RPM	32.1
	Torque	Nm	5.596	Nm	21.142	Nm	39.131
Maximum output power		W	23.64	W	144.58	W	262.66
Resolution		Step/turn	304,000	Step/turn	502,000	Step/turn	502,000
Gear ratio		-	304	-	502	-	502
Backlash		arcmin	3.5	arcmin	3.5	arcmin	3.8
Interface		-	RS-485 / CAN	-	RS-485 / CAN	-	RS-485 / CAN
Operating temperature		˚C	5~55	˚C	5~55	˚C	5~55

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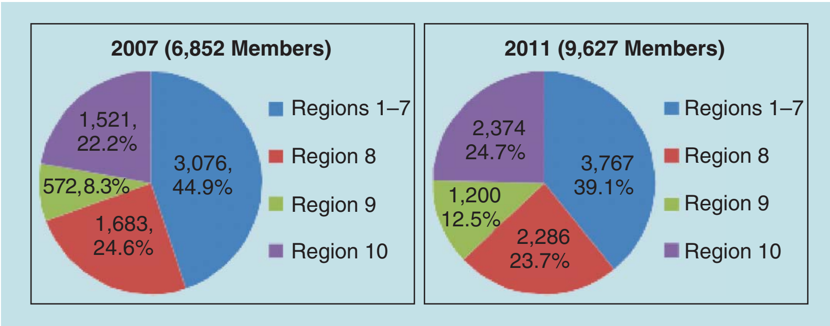

Figure 3. RAS membership by IEEE region in 2007 and 2011. Regions 1–7 (USA and Canada), Region 8 (Europe, Middle East, and Africa), Region 9 (Latin America), and Region 10 (Asia and Pacific).

membership in Region 9 was relatively small in 2007, it has more than doubled through 2011. Region 10 has had significant growth as well, and recent statistics have shown a marked increase in this region's membership for 2012.

The question certainly arises as to what has contributed to this dramatic growth in IEEE RAS membership. Some of the programs and policies of former President Kazuhiro Kosuge and the Executive Committee, with Stefano Stramigioli as the vice president for member activities, have had a strong impact on this growth. In 2011, the Society reduced its membership fee by more than 50%. This, coupled with the IEEE program to offer a substantially reduced e-Membership rate in developing nations, has made RAS membership much more affordable. President Kosuge also established the Distinguished Ambassadors Program to introduce the Society in developing regions. After the 2011 IEEE International Conference on Robotics and Automation (ICRA) in Shanghai, China, a number of officers of the Society visited several universities in China and combined a short introduction to RAS with their technical lecture. It was considered a huge success by everyone involved.

In our estimate, another contributing factor is the ground swell of interest in robotics and automation, even by precollegiate students. Increasing interest of elementary and secondary school students as well as undergraduate university students has been stimulated by robotics use in science, technology, engineering, and mathematics (STEM) education. Robot competitions are also attracting students from almost all regions of the world.

Major Redesign of Our Web Site

We are excited about the phenomenal growth in the membership of the Society, and we are thinking very hard about the services that we offer to our members and how we can improve them. The Society is currently undergoing a major redesign of our Web site, and we have contracted with D2 Creative, Inc., Somerset, New Jersey, to work with us. The Web site promises to be more user friendly and provide members and volunteers with additional resources when it is rolled out in the new year.

We appreciate the feedback you gave us through the recent Society survey, which gives us a better understanding of our members' needs. We will follow up with a town hall meeting at ICRA 2013 in Karlsruhe, Germany, and we hope that many of you will participate.

Also, feel free to contact any of the 18 Administrative Committee (AdCom) members, whom you have elected to govern the Society, if you have any ideas that you would like to discuss with them. They are elected from the three major regions of the world. Six are elected each year for a three-year term. The current members of the AdCom are listed in each issue of the Magazine (page 97 in this issue), along with their affiliations. They would welcome your suggestions, listen to your grievances, or appreciate your words of encouragement on the volunteer leadership that they are offering in the Society.

One final word: I very much appreciate your continuing interest and support for RAS. I hope that you will be active in the Society so that we can w ork together to advance the robotics and automation field, whose best days are yet ahead.

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Robot Challenge

By Stephen Balakirsky, Sachin Chitta, George Dimitoglou, Jason Gorman, Kayla Kim, and Mark Yim

The 2012 IEEE International Conference on Robotics and Automation (ICRA) Robot Challenge again proved to be an exciting venue where researchers showcased the latest state of the art in robotics. In addition to this year's challenges, the conference also featured a special session where the 2011 teams were able to present and discuss their competition-related research. The challenge has grown to include five individual events, 28 teams, and close to 100 participants. Each of the events is detailed below.

The Virtual Manufacturing Challenge (VMAC) made its fourth consecutive appearance and had the highest number of teams participating ever. The competition included two events, a mixed palletizing and an intrafactory mobility challenge. Mixed palletizing is an example of the three-dimensional (3-D) cutting stock problem, a variant of the combinatorial nondeterministic polynomial-time hard (NP-hard) knapsack problem. Teams were required to generate a pallet-stacking plan from order files and constraints provided by an industry partner. The team's palletstacking plans were evaluated by National Institute of Standards and Technology (NIST)-developed metrics for pallet quality, which included criteria such as the pallet's center of gravity, density, and package interlocking.

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Figure 1. Team members from the DARwIn-OP Humanoid Application Challenge.

The intrafactory mobility challenge aimed to address the need for factory robots to operate in unstructured environments amongst dynamic obstacles, as seen in numerous assembly plants and distribution centers. Teams were tasked with docking a rear-wheeled Ackerman steered robot with a conveyor system, picking up packages for transport, and then delivering these packages to unloading stations in the factory.

Six teams from five institutions and four countries participated in VMAC. The winner of the mixed palletizing challenge was the team from Jacobs University, Bremen, Germany, while Drexel University, Philadelphia, USA received an honorable mention. The team from the University of Zagreb, Croatia, won the intrafactory mobility challenge.

Another first from VMAC this year was the organization of a guest lecture during the last day of the competition. Erik Nieves, technology director at Yaskawa Motoman Robotics, gave a very interesting talk: "The Challenges of Robotics in Logistics—An Industrial Perspective." This event was cosponsored by the IEEE Robotics and Automation Society's Washington, DC/ Northern Virginia Chapter. This is the

Figure 2. Team members from the Mobile Microrobotics Challenge.

start of a new tradition that will reinforce and further promote VMAC's ties with industry, research, and government partners.

The Dynamic Anthropomorphic Robot with Intelligence-Open Platform (DARwIn-OP) Humanoid Application Challenge is based on developing creative research and novel applications for humanoid robots in an open-source community for cooperative research. This year was the first open challenge using DARwIn-OP, and nine teams from across the United States, Canada, and Spain participated (Figure 1).

Each team's 20-min presentation was composed of a demonstration of their application followed by a question and answer session open to judges, the audience, and fellow participants. The challenge was peer reviewed based on creativity (40%), technical skills (30%), and overall completeness (30%).

The winner was a team from the University of Manitoba, Canada. Their entry featured Jennifer—the first member of their robotic ice hockey team. Even though superficially similar to soccer, ice hockey provides several unique challenges that make it a very interesting research topic. First, movement on skates on ice is very different from walking. New walking gaits that emphasize side-to-side movement needed to be developed. Second, the movement of the puck requires more accurate and complex movement than dribbling a ball, since the stick needs to move the puck from side to side. Third, the blob detection needed to be replaced with a region-based segmentation and shape-detection algorithm. The winner was awarded one DARwIn-OP humanoid robot, LabVIEW Robotics Software, and Webots Pro.

The challenge also featured an online competition. The winner from Purdue University featured two tic-tac-toe playing DARwIn-OPs. The goal of this entry was to take advantage of the capabilities of DARwIn-OP, engage the ICRA audience with artificially intelligent robotic game play, and contribute to the DARwIn open-platform community. Their

Figure 3. A student from Johns Hopkins University builds a robot from a kit of parts in the Modular Robotic Challenge.

research includes robot-to-robot interaction, image recognition and processing, possible robot-to-human interaction, robotic movement, and the development of the artificial robotic adversarial personalities. All finalists were awarded a Bioloid Premium Kit, a LabVIEW Robotics Module, or a Webots Edu.

The Mobile Microrobotics Challenge (MMC) is focused on driving innovation in the design and control of robots that are smaller than a millimeter. Applications for this technology include medical diagnostics and therapeutics, mobile sensor networks, and micro- and nanomanufacturing. The challenge was started in 2007 by the NIST and has been held as part of the ICRA Robot Challenges since 2010. The challenge goal is to accelerate the adoption of this technology by industry by solving critical technical barriers through structured competitions. Previous challenges have focused on basic functionalities, including robot speed and microassembly of components using simple fixturing. In 2012, the challenge had two independent tasks—the mobility task, in which the microrobot must navigate a figure-eight course in the shortest time, and the microassembly task, where the robot has to assemble groups of triangular components without the use of fixtures.

Figure 4. The PR2 robot being used by the world team in the 2012 ICRA Mobile Manipulation Challenge to clear a table.

Nine teams from four countries (Canada, the Czech Republic, France, and the United States) participated in the challenge, making it the largest MMC event to date. (Figure 2). The demonstrated microrobot technologies included laser-controlled bubble robots and robots actuated using dielectrophoresis as well as the more common electromagnetic microrobots. A team composed of members from the Institut des Systèmes Intelligents et de Robotique, Franche-Comté Electronique Mécanique Thermique et Optique—Sciences et Technologies (FEMTO-ST), and the Centre National de la Recherche Scientifique. France, won the mobility task with an electromagnetic microrobot that completed the "figure-eight" track in less than 0.5 seconds. Every team was able to complete the figure-eight track, indicating that this functionality is now a solved problem.

The microassembly task was won by Carnegie Mellon University (CMU) using an electromagnetic microrobot that was able to place at least two triangles into an assembly in all three of the trials. Unlike the mobility task, the microassembly task remains an open problem and will likely appear in future challenges.

The Modular Robotic Challenge has run four times since 2008. The rules are fairly simple with an unknown robotic task to complete in roughly 4–6 hours. Competitors can bring anything they want that fits in 64 linear in (e.g., a suitcase) and weighs less than 50 lb total. This constraint includes robot modules, power supplies, tools, computers, raw materials, duct tape—everything.

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This challenge develops, tests, and validates

1) rapid robot prototyping and design methodologies
2) software for rapid teleoperation and new programming paradigms
3) adaptability/generality of robotic hardware and software
4) user interfaces (both hardware and software).

In 2012, three teams participated: Harvard University, Johns Hopkins University, and the University of Colorado at Boulder (Figure 3). All three teams used CKBot robotic modules supplied by the GRASP lab, University of Pennsylvania. This year's challenge shared the same task as the Mobile Manipulator challenge: serving sushi. The only differences were that the robots had to be constructed on site and could be teleoperated. Points were awarded for placing food and utensils and busing tables. Points were lost for dropping items.

In the end, the three teams were successful in building a robot to carry out human-scale tasks and served three plates of maki, three plates of nigiri, two cups, and two utensils as well as busing six items (plates, cups and spoons). Unfortunately, they also dropped a dozen plates (nine of them with real sushi). Building a robot capable of human-sized tasks in 4 hours was the most difficult part, yet all teams succeeded in this. The area needing most work was reliable control and manipulation of the items even when teleoperated.

The Mobile Manipulation Challenge, also called the "Sushi Challenge," was held for the first time. Yesterday's Sushi was a sushi restaurant operated by autonomous robots. The robots were expected to clean dirty dishes off tables, set dishes and silverware on a clean table, and serve sushi. The intent of this challenge was to push the state of the art in autonomous mobile manipulation, integrating the state of the art in perception, manipulation, navigation, and other capabilities. The teams participated in the challenge using the PR2 robots supplied by the organizers (Figure 4).

Interested participants were first invited to take part in a preparatory workshop for the Challenge at the University of Freiburg. Over 30 participants from around the world took part in this workshop, where they were able to program the robots to stack and unstack dishes, clear tables, lay place settings, and pick up objects off a rotating turntable sushi boat, building on a base of software built by researchers from Willow Garage, the PR2 Beta Program, and the robot operating system (ROS) community.

The participants in this workshop got together to form two teams for the ICRA Challenge: a world team (including students from Technische Universität München (TUM), Brown University, and KU Leuven) and a team of graduate students from the University of California, Berkeley. Both teams performed admirably, successfully performing a subset of the tasks, including recognizing common kitchen objects, navigating autonomously while carrying objects, and tracking and picking up moving objects. A team from Willow Garage, including interns from the Massachusetts Institute of Technology, the University of Southern California, the University of Pennsylvania, and CMU also demonstrated a complete integrated demonstration carrying out all the tasks outlined in the challenge. The software implemented by participants in the challenge, providing capabilities in 3-D navigation, semantic mapping, object recognition, and manipulation, is available open source from the challenge Web site (mobile-manipulationchallenge.org).

The teams and organizers are looking forward to continuing these competitions at ICRA 2013. In addition, we anticipate that a special session will be held to showcase competition technologies. For more information, visit the ICRA 2013 Web site at www.icra2013.com.

Passenger-Carrying Industrial Robotics

By Gino De-Gol

On 23 May 2012, the Innovation and Entrepreneurship in Robotics and Automation (IERA) Award for Innovation and Entrepreneurship in Robotics and Automation was awarded to Gino De-Gol of Robocoaster Ltd. for his work in industrial robotics certified for passenger-carrying operations.

The Dawn of Robotic Rides

The pace of development in modern industrial robotics over the last decade, particularly with regard to payload, motion capability, and safety systems, has been dramatic. Similarly, the developmental pace of modern amusement ride systems over the same period has also developed significantly in terms of show technology and ride transport systems (Figure 1).

The use of robotic motion systems in the entertainment sector was virtually nonexistent.

It became apparent to an English robotics specialist during the turn of the new millennium that, despite an ever-increasing need for sophisticated motion systems in the amusement ride industry, the notion of modern industrial robots has been largely ignored, especially in the context of potential passenger-carrying applications.

Having worked on the industrial and automotive equipment supply side for more than 20 years, De-Gol had acquired a strong working knowledge of the capabilities and safety of modern manufacturing robotics. Recently, recognition also dawned that the payload and integrated safety capability was opening a new window of opportunity for a long-held ambition to develop a viable robotic amusement ride. An initial search for the use of robotics in the amusement industry appeared to support the hypothesis, as the use of robotic motion systems in the entertainment sector was virtually nonexistent.

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Figure 1. RoboCoaster G1.

As the amusement ride sector was a matured and well-funded industry in the west, with high guest experience expectations and significant income, the opportunity to develop a product with a unique selling proposition was evident.

To study the proposition further, RoboCoaster Ltd. was formed in December 2000 with the express intention of investigating the technical and commercial viability of passenger-carrying industrial robotics in the field of entertainment.

The Product Genesis

The amusement ride industry can be segmented into categories relating to the size of the venue or park and the attending rider capacity per hour per item. This can be approximated as follows:

1) family entertainment centers (FECs): 20–200 riders per hour;
2) small to medium-sized amusement parks: 50–1,200 riders per hour;
3) large parks and theme parks/resorts: 1,000–2,500 riders per hour.

As the highest payload class robot available at the outset of the development exercise was in the order of 500 kg, the best prospect for passenger transport capability (including a complete passenger safety module) was determined to be a two-passenger robot solution utilizing a robust and secure passenger module.

Despite the premise of the project being quite simple (to put seats at the end of an industrial robot), the practice for a viable certification path was, of course, much more complex. The proof cases for an absolutely safe motion platform for passenger operations takes robot design into entirely new areas of design and performance.

- Many new and unanticipated single-point failure modes must be mitigated.
- Fail-safe systems (including predictable deceleration curves) are needed.
- Full finite element analysis (FEA) and failure mode and effects analysis (FMEA) of the structure and lifetime fatigue effects (to new norms) are needed.
- Inertial stresses imparted to the passengers are to remain within set physiological limits.

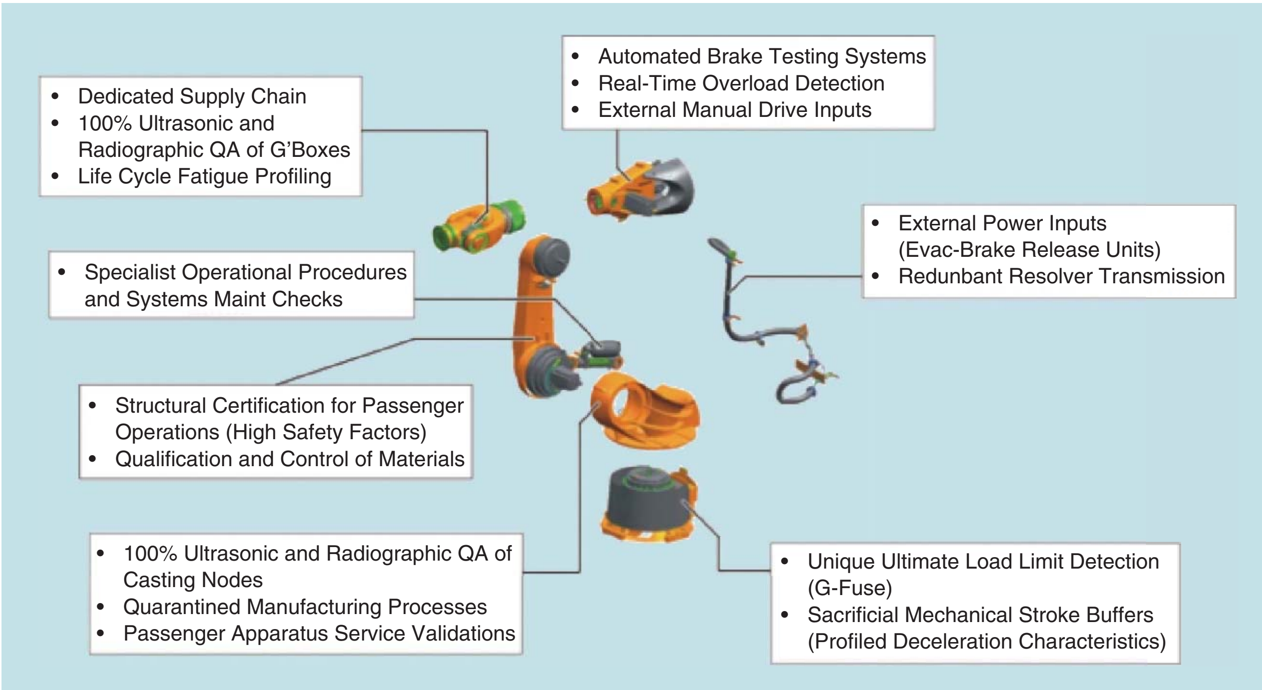

Figure 2. RoboCoaster certification requirements.

- Evacuation protocols should be developed under set conditions, including complete power failure scenarios.

The increased requirements for structural load limit safety factors led to the re-engineering and adjustment to key structural nodes of the original robot manipulator, taking the entire robot structure to a much higher safety plane than is required for normal industrial use (Figure 2).

A sophisticated radiographic and ultrasonic quality inspection regime was initiated, validating the integrity of all structural and drive elements (including castings, bearings, gearboxes and drivelines) (Figure 3). The robot motion planning and safety controls were also supplemented to ensure that ride accelerations imparted to passengers never exceed the preset physiological limits. This in particular was a challenge for a freely programmable motion system and a special protocol was developed to ensure that the orientation and compounding of motion vectors were always taken into account.

The prototype robot was demonstrated in November 2001, and the first RoboCoaster certified for passenger use debuted the following year at the Industry Showcase Trade Exhibition (the International Association of Amusement Parks and Attractions Show in Orlando, Florida). RoboCoaster subsequently won the Best New Technology Applied to Amusements Award 12 months later for the Legoland Billund Power Builder attraction.

A Different Approach

At the outset, it was apparent that the motivation for producing a robot for the industrial market would be very different from producing one for an amusement offering, particularly from the developer/supplier point of view.

The key considerations for industrial robot products can be summarized as follows.

Key Product Criteria: Industrial Robot Sector

1) Price (sub median cost)
2) Speed and acceleration (fastest possible)
3) Repeatability (sub-millimeter range)
4) Reliability (MTBF > 70 k hrs)
5) Safety (arrest and secure motion)

Price Performance Ratio

Whereas, the amusement sector key considerations would be:

Key Product Criteria: Passenger Robot Sector

1) Safety (deterministic safety strategies–evacuation capability)
2) Certification (passenger approvals, crash testing, and permits)
3) Structural integrity (single point failure mitigations)
4) Reliability (recovery from mechanical and control failures)
5) Speed and originality (governed by biomedical safety limits)
6) Commercial (robust legal and PL requirements)
7) Price (close to median point–premiums for originality)

Experience Safety Ratio

Whereas the key driver for a successful industrial robot offering can be summarized as the now well-established "price/performance ratio," the

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The 21st Mediterranean Conference on Control and Automation, **MED'13**, comes back to its birthplace, Chania, Crete. **MED'13** aims at providing a unique opportunity for the academic and industrial community, federal and state government, funding agencies, the private sector, qualified representatives from other organizations, to address new challenges, share solutions and discuss future research directions in the area of control and automation. Focused interests of diverse groups involved in basic and applied research and development will be discussed. A broad range of topics will be covered in the Conference, following current trends of combining control/systems theory with software/communication technologies, as well as new developments in robotics and mechatronics, with the goal of strengthening cooperation of control and automation scientists with industry. For information about **MED'13**, visit http://med13.du.edu.

MED'13 will be held at the Minoa Palace Resort and Spa (http://www.minoapalace.gr), a luxury five star beachside resort. The resort is situated in the cosmopolitan area of Platanias, 12km west of the picturesque town of Chania and about 30 min drive from the Chania International Airport. The resort offers majestic views of its surrounding countryside and the White Mountains. To the north, the resort enjoys panoramic views of the endless golden beach of Platanias with the shimmering sapphire blue Aegean beyond. Guests have immediate access to the sandy beach in front of the resort. For information about Chania, visit: http://www.chania.edu/tourism and for Greece, visit: http://www.gnto.gr.

MED'13 topics of interest include, but will not be be limited to:

Adaptive control
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Process control
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IMPORTANT DATES: The Program Committee is soliciting contributed technical papers for presentation at the Conference and publication in the Conference Proceedings, as well as proposals for invited sessions/papers/talks by topic of interest. *Accepted papers will appear in the conference digital proceedings and in IEEE Explore.*

February 1, 2013: Contributed papers, invited session proposals, Workshop / Tutorial proposals, Due.
April 15, 2013: Notification of Acceptance/Rejection.
April 30, 2013: Final, Camera Ready Papers, Due.

PAPER SUBMISSION: Papers must be submitted electronically using https://controls.papercept.net. The guidelines are given at the MED'13 Web site. Full papers should be submitted in standard IEEE double-column format for conferences. The first page of the paper, centered on the top below the top margin, should include the paper title, the authors' names and their affiliations, an abstract, and keywords. Six pages are allowed for each paper. Up to two additional pages will be permitted for a charge of €125 per additional page. Illustrations and references are included in the page count. Submitted papers will undergo a peer review process, coordinated by the Program Chairs.

Invited Sessions: A Summary Statement describing the motivation and relevance of the proposed session, invited paper titles and author names must be e-mailed by the organizer(s) to the Invited Sessions Chair by February 1, 2013. Authors must submit ***full versions of invited papers*** electronically. Each such paper must be marked as 'Invited Session Paper'.

Workshops – Tutorials: Proposals for workshops - tutorials should contain the title of the session, the list of speakers, and extended summaries (2000 words) of their presentations. Proposals must be sent by e-mail to the Workshop/Tutorials Chair by February 1, 2013.

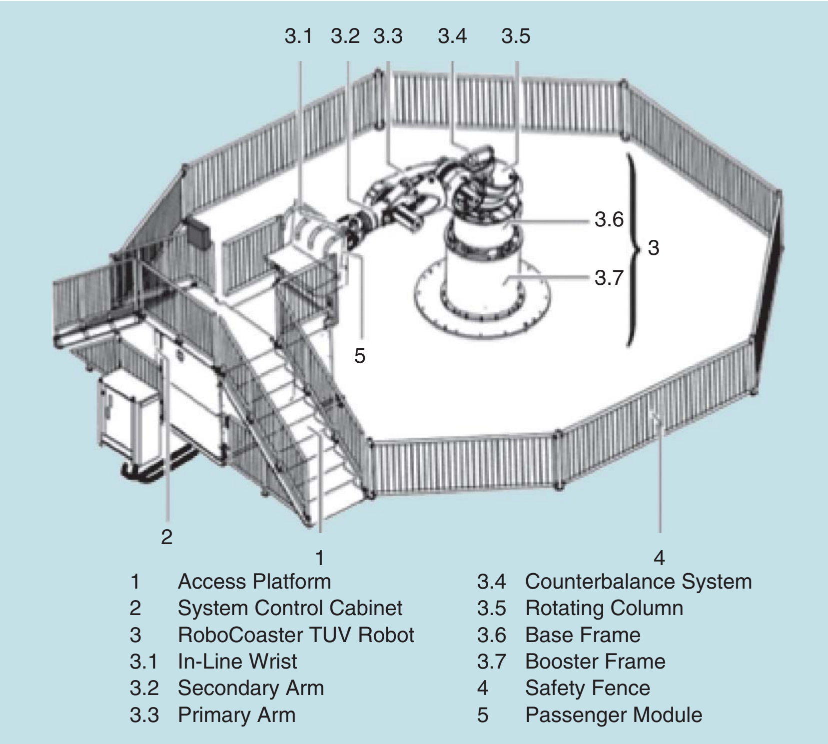

Figure 3. RoboCoaster G1 solution.

amusement ride sector, however, would be better described as the experience/safety ratio. The two approaches serve to underline the more complex requirement for passenger operations, i.e., how to guarantee the successful evacuation of a passenger in the case of a mechanical failure, which would never be considered in an industrial application.

Robots as a motion solution in the field of entertainment, and passenger-carrying in general, are now considered a safe and accepted approach.

Figure 4. RoboCoaster G2.

After a very successful period of testing and collaboration with the German robotics giant KUKA Roboter, the RoboCoaster became the world's first application of industrial robotics being fully certified for passenger-carrying operations, and RoboCoaster's sales campaign began.

The RoboCoaster TÜV robot is, to date, the only application of industrial robotics being adapted and certified for passenger-carrying operations, and has been widely adopted in amusement and theme parks around the world with an amazing amount of passengers already carried by the beginning of the 2012 season.

This pioneering work with regard to safety certification and approvals has led to other passenger-carrying market opportunities to be explored, including the medical and low-cost motion simulation markets, both of which are now being actively exploited.

Breaking into the Major Parks

It was recognized at an early stage that, to have a ride solution capable of applications in major theme parks, a capacity capability in the 1800 to 2500 theoretical hourly ride capacity (THRC) range was necessary. To be able to achieve rider volumes of this magnitude, a recirculating track system carrying the robots would be necessary.

The solution to this challenge was the second generation of RoboCoaster (G2) incorporating autonomous tracked robot transporter solutions (shown in Figure 4). The RoboCoaster robots were also modified to a reduced axis set (four axes) to provide an increased payload, thus accommodating four passengers per robot manipulator. Such a configuration allows the recirculation of the robots through an attraction and moving station walkways, providing capacities in the order of 2,000 riders per hour. This approach, along with various other developments on the show side, was to become the now famous Harry Potter and the Forbidden Journey ride in Universal Orlando.

Third and fourth generation evolutions are expected to similarly impact the market from mid-2013 onwards.

Taken for a Ride

The format has a perfect operational safety record, and has to date carried a combined estimated 64 million passengers worldwide. Although the installed global capacity in 2012 is already 18 million passenger transports per year, this is planned to grow to over 35 million passenger transports per year by 2016.

As a result of the RoboCoaster project, robots as a motion solution in the field of entertainment, and passenger-carrying in general, are now considered a safe and accepted approach, and further fields of study and application are sure to follow. The perception that robots are not to be used to move persons has firmly been dispelled, and a whole new market segment and genre has been created in the field of service robotics.

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[1] Best New Technology—IAAPA Award. (2004, Oct. 24). [Online]. Available: http://www.kuka-robotics.com/usa/en/pressevents/news/NN_041020_IAAPA.htm

[2] IAAPA Editorial. (2003, Mar.). [Online]. Available: http://www.iaapa.org/industry/funworld/2003/Mar03/Features/Robotic%20Revolution /RoboticRevolution.html

Lightweight Robot for Everybody

By Dr. Esben H. Østergaard

Automation in small enterprises? Until recently, no one would ever have imagined this. The reasons are obvious. So far, automation has been too expensive and the available robots too cumbersome, so only specialists have been able to program them and the operating integration has been difficult. Those days are over now. Our robot fits this gap!

It all started with a vision. I worked at the Danish Maersk McKinney Moller Institute. Together with other engineers and researchers, I recognized the increasing need for a new kind of robot in the production industry. Kasper Stoy, Kristian Kassow, and I decided to pursue this idea and form a company to develop a universal robot. Thus, we founded Universal Robots in October 2005. Our young company put in a lot of effort in driving the project in the first three years. In the fall of 2007, we tested a prototype robot arm at a greenhouse near Odense, Denmark. We had set up a complete working solution for the robot in just one evening: moving trays of pottery from a conveyor to a table in stacks of three. With new management and extra financial support, Universal Robots started to grow into the company that is well known today. Our development and production headquarters is still located in Odense. But now our robot arm is distributed by more than 80 partners in over 40 countries in four continents. Our first designed robot, the UR5, has an even bigger brother today, the UR10 (shown in Figure 1), with a greater reach and the capability to lift heavier pieces.

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You might ask, "What is so special about this product?" The UR5, just like the UR10, can be used in various fields. You may find it useful in the kitchen production as well as in the painting industries. There are also robot arms from Universal Robots working for automotive suppliers, and even in the medical industry. That's what makes our robots literally universal! Because of its low weight—the UR5 only weighs 18 kilos—the robot can easily be moved around within the production area. This means that the same robot can do "pic-and-place" jobs for one production step and then can be moved to some other place doing a different kind of work. The arm itself is a small and user-friendly six-axis industrial robot. The robot's designation comes from the weight it can lift. The UR5 can handle a load of 5 kg at a time, the UR10 accordingly 10 kg.

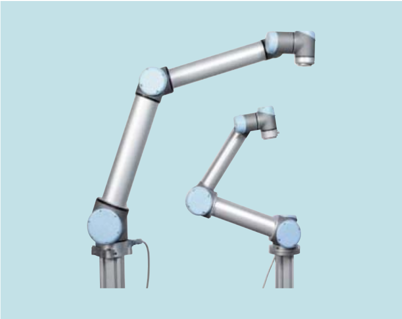

Figure 1. UR10.

Still, one more thing was very important for us during the process of developing the universal robot. We wanted to make it as user friendly as possible. So, we decided to install a software and an intuitive graphical user interface that makes the robot simple to program. Within a very short time, the robot can be integrated into any production process. Our experience shows that this is generally done in a few hours. Even reprogramming is fast and uncomplicated—no information technology specialists are required. It can be accomplished by any technical staff.

But, what makes our robot arm really special is the fact that it can operate without screening in accordance with current regulations. The "collaboration mode" takes care of the safety of staff working in the vicinity of the robot. As soon as an employee comes into contact with the robot arm, and if a force of at least 150 N is applied, the robot arm will automatically stop operating. This makes the robot ideal for use in production facilities with limited space.

Of course, we also had to keep the price in mind; small-and medium-sized enterprises (SMEs) demand a fast return on the investment. Besides the robot's low initial cost, it also operates very cost-efficiently. The robot becomes profitable within an operating period of only 6–8 months. That shows another big advantage of our robots: even SMEs can gain access to automation, which has been too expensive for them so far.

Looking back, I have to say that only seven years after the foundation of Universal Robots, I am very proud that our vision of an affordable robot has already become a reality. We even won the Invention and Entrepreneurship Award at the 2012 exhibition, "Automatica!" Of course, we are not resting on our laurels now. In the near future we are going to expand our presence in to the North American and Eastern European market. Also, one thing is clear: we will always stick to our mission and teach companies all over the world our new approach to robots. Even small companies can use robots—we want to demonstrate to them that a robot can be very flexible and a helpful tool, rather than a machine that takes away the job of a human.

High Tech, Low Sales!

By Erwin Prassler

After 25+ years of research and development in service robotics, it sounds like mantra when members of the robotics community praise and bless the results of their work as a remedy for many of the inconveniences of daily life. It seems, however, that mankind today does not suffer from fewer inconveniences than it did 20 years ago, but rather more. Robotics also hasn't done much to change that. If every promise to "make life easier" made in these past 25 years had been turned into a real service robot product, we would almost live in paradise.

Unfortunately, robotized paradise still seems to lie some ways ahead of us. Admittedly, there are some devices that have been on the market for a while, which at times call themselves service robots: robotic floor cleaners, pool cleaners, lawn movers, and some toy robots. But is that it? What is beyond that? Anything that is of use to regular citizens which they may be able to buy? Will we soon be surrounded by hundreds or thousands of personal robots, which are omniscient universal problem solvers and servile providers of everyday services? Will we be served by robot butlers, treated by robotic nurses, entertained by robotic clowns, and consoled by robotic friends?

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Never say never! But honestly, are we really willing to spend the budget for a sports car or more to buy a robot, and if so, do we really want a robot to become our friend? Doesn't that sound a bit insane? Why not choose the sports car as a friend?

Cynical statements aside, the question is, where is robotics research heading and, in particular, where is that branch of robotics research heading that deals with nonindustrial robots, often called service robotics? Does this branch have only visions like the one of a personal robot or a robot companion, or does it also have an agenda that links basic research to products on the shelves in warehouses, or at least indicate that such a link is feasible?

Taxpayers don't want to give their hard-earned money away for visions, neither for political nor for technical ones. They expect affordable, useful devices that ease their lives either at work or at home, and they expect publically funded research to eventually generate new industries and new markets offering them new interesting jobs. We are not talking about high-tech robots that explore Mars, assist in surgeries, or populate battlefields. We are talking about robots that ease the life of mankind in everyday environments.

It can hardly be explained to the taxpayers that 25 years of research has not led to more than some robotic lawn mowers, floor cleaners, pool cleaners, and toys. In spite of the outstanding achievements that robotics research has made in the past 25 years in the area of service robotics, it seems that robotic research either needs to recalibrate its promises, its research agenda, or both. A good starting point for such a recalibration is a root cause analysis of the current situation.

One obvious major reason for the rather modest transfer of robotics technology into consumer products is the fact that system design, system building, and system integration targeting a concrete product idea all too often is not considered robotics research. One can rarely find publications on new, economically competitive robot applications. So, for a Ph.D. student or an assistant professor working toward tenure, there is no good reason to waste his or her time on system design. What makes things worse is the fact that designing a complete system or a complete application takes significantly more effort in terms of time and other costs than designing a new algorithm. Also, it requires a broad range of interdisciplinary knowledge ranging from mechanical and mechatronic engineering, electrical engineering, control theory, software engineering, and computer science in general, to artificial intelli-gence and cognitive sciences. It is very rare that one single person has such a broad body of knowledge. So, it requires a whole team to subscribe to an activity which may not contribute to one's publication list.

A second major reason lies in the fact that technology development is rarely affected or constrained by economic considerations. It may sound counterproductive and creativity-inhibitive to condition technology development on economic considerations. In service robotics, however, this most likely will determine economic failure or success irrespective of the scientific quality of the developed system. For example, in the area of cleaning robotics, we counted around two dozen professional cleaning robots between 1985 and 2005, which all turned out to be technological success stories but economic failures. The indicated price tag of these systems was between US$30,000 and US$50,000. None of the robotized solutions could economically compete with a manual cleaning service.

A third reason is the lack of low-cost technology. Robot technology seems to be notoriously expensive. iRobot's Roomba can be seen as a milestone in robotics since it was the first domestic robot appliance that came on the market with a price tag of a regular appliance. Given the high cost for (high-quality) components, it is a challenge to design service robots in particular in a domestic environment at a price that people are willing and able to pay. One might say that the principle of "economy of scale" will solve this problem. Such a statement, however, is rather naïve, given that, for example, a purchase volume of 1,000 dc motors compared to ten makes a price difference of 25% to 30%. With this, the price of a personal robot may go down from US$250,000 to US$175,000. That is just the difference between different models of luxury sports cars. So, economy of scale will not solve the problem. What is needed is research towards low-cost robotics.

The above three reasons are certainly not the only ones for the rather low pervasion of our everyday life with service robots, but they have significantly contributed to this situation. In a follow-up to this column, we will discuss what can be done to change the situation for the better. Stay tuned!

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Robot Web Tools

By Brandon Alexander, Kaijen Hsiao, Chad Jenkins, Bener Suay, and Russell Toris

The robot operating system (ROS) has provided roboticists with a robust, cross-platform middleware, and has also given researchers from around the world a common place to share their ideas and reproduce each other's work. Within the growing ROS community, developers have created software on a wide range of robotic platforms, from Willow Garage's sophisticated PR2 mobile manipulator to LEGO's simple and widely available NXT.

However, while the community's efforts have facilitated significant milestones in robotics research, the core ROS middleware still requires a considerable learning curve, including a general understanding of UNIX systems and languages such as C++, Python, or Java. To generate interest in robotics in a larger, more general population, we must remove this requirement. The World Wide Web provides both a guiding example and a path for broadening the reach and accessibility of robotics. With the goal of building a larger community of robot Web app developers, we describe recent efforts to expose the functionality of ROS via common Web development tools such as JavaScript.

Rosbridge as an Access Point for ROS

Rosbridge provides an application-layer network protocol for robotics, allowing arbitrary, non-ROS client processes

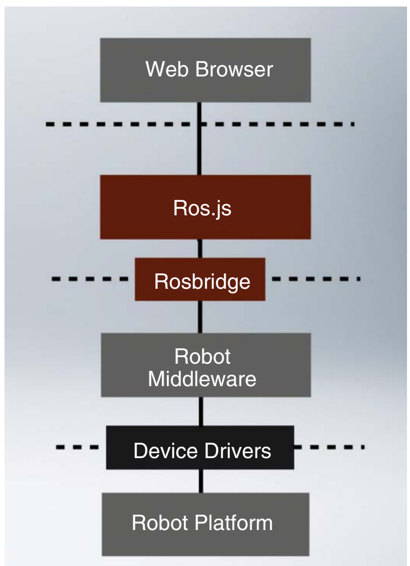

Figure 1. Pipeline for a typical Web application using rosbridge.

(including Web interfaces) to interoperate with ROS processes. Specifically, rosbridge allows clients to publish and subscribe to ROS topic messages, and to invoke ROS services in the server's runtime environment, by transporting JSON-formatted messages over TCP sockets and WebSockets.

The beauty of rosbridge is that its clients are language-independent. That is, rosbridge clients can be written in any language that supports WebSockets. Furthermore, rosbridge itself does not limit clients to ROS. The reference server implementation mentioned above is written for ROS, but the rosbridge protocol is a specification and, as such, is not tied to any programming language or runtime. The JSON-based rosbridge protocol has been designed to enable data publishing, subscribing, and service invocation between any combination of clients and servers, regardless of platform. Implementations have been successfully created using Linux, Windows, Android, iOS, Arduino, common Web browsers, and more.

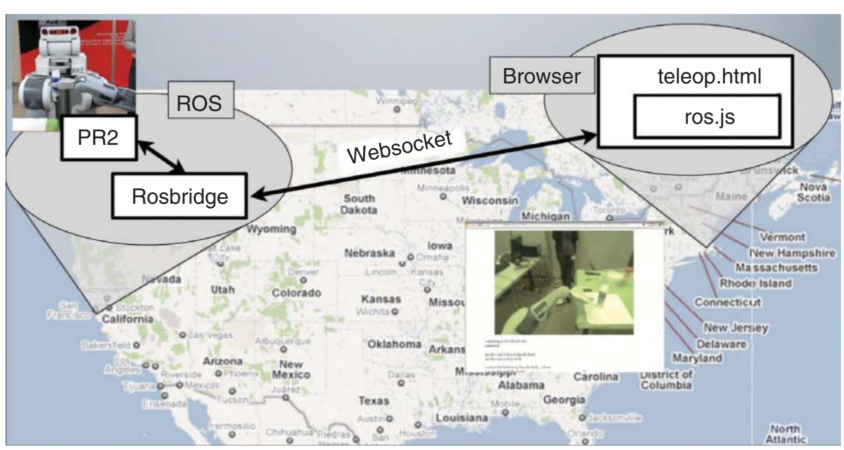

Figure 2. Connection diagram for a PR2 teleop application.

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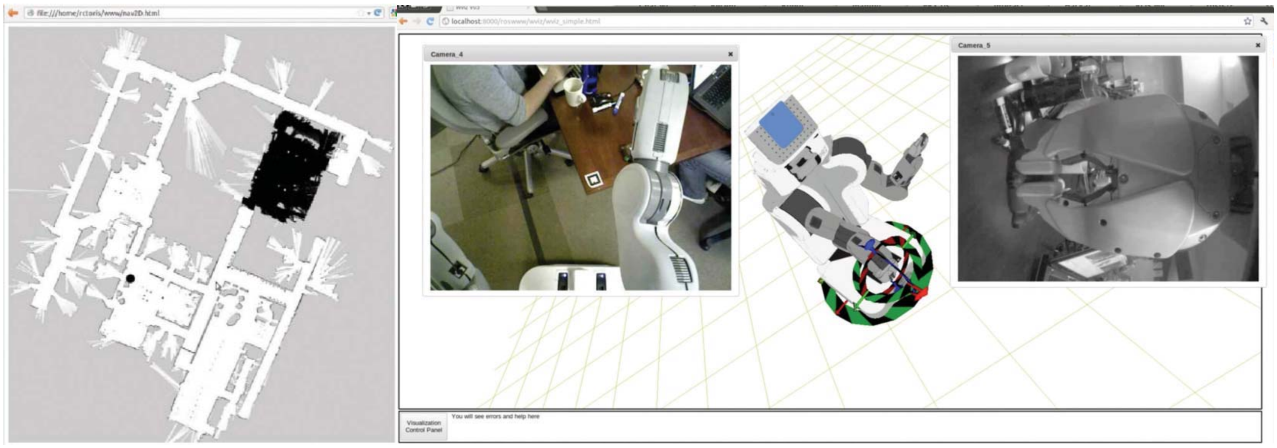


Figure 3. Scavenger hunt Interface 1: wviz-based Web interface that provides autonomous map navigation, camera streaming, and interactive marker tools for moving the arms, base, torso, and head.

A stable and robust implementation of a ROS rosbridge server (as well as a number of useful Web tools) is available in the rosbridge_suite stack on ros.org (http://www.ros.org/wiki/rosbridge_suite), and a specification of the rosbridge protocol is available at http://rosbridge.org.

Ros.js

For integration with modern Web tools, a JavaScript library named ros.js was built to facilitate communication between the browser and rosbridge. A JavaScript Web application running in the browser can communicate with a ROS application running on a remote robot or server using ros.js and rosbridge.

Ros.js is designed to be lightweight and event-based. Its lightweight code base allows easier integration within existing, large-scale JavaScript applications, in addition to allowing other robot Web tools to build off of it. The event-based library will emit an event on the basis of feedback from the robot, server, or user. An event-based ros.js allows for a more responsive UI and decouples the ros.js module from other JavaScript modules (Figures 1–2).

Wviz

Wviz (short for Web visualization) is a robot and sensor data visualization tool that runs in a Web browser. Similar to RViz, it renders 3-D models of the robot and sensor data, lets the user add or remove different sensor data displays, and modifies the properties of each display (e.g., image size, color, topic, TF, etc.).

Although wviz is designed to be generic, creating a customized version of wviz is fairly straightforward: necessary widgets and displays (such as image, robot model, and interactive markers) can be called from the main HTML file and loaded with the application, as opposed to being added dynamically by the user. Wviz and related packages can be found in the bosch_web_visualization stack.

Robot Web Hackathon: PR2 Scavenger Hunt

During the week of 13 August 2012, a Robot Web Hackathon was held at Willow Garage to gather people from the ROS community interested in creating and using robot Web tools. Using Web teleoperation of a Scavenger Hunt task as a motivating example, the event's focus was to create and test a set of community tools for creating robot Web applications. Attendees included faculty, students, and researchers from Brown University, WPI, Georgia Tech, Bosch LLC, and Willow Garage, primarily drawn from the current rosbridge user community.

The goals for the week included improving and testing a new version of rosbridge, creating a commonly-agreed-upon version of ros.js, incorporating both into wviz and other existing robot Web applications being developed by the participants, and, finally, using the results to create Web interfaces for teleoperating PR2 robots in a scavenger hunt. Two interfaces were created to allow participants to locate, pick up, and photograph a variety of scavenger hunt objects. These interfaces were used successfully by several on-site participants, as well as a remote user from across the country.

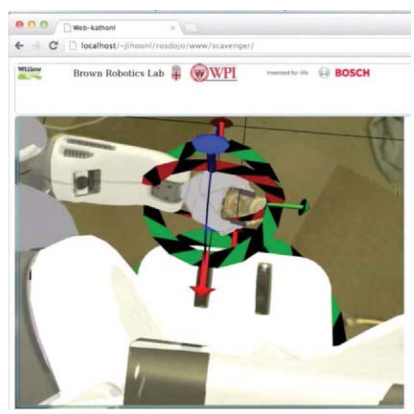


Figure 4. Scavenger hunt interface 2: interactive marker tools for moving the robot overlaid over the robot's camera view.

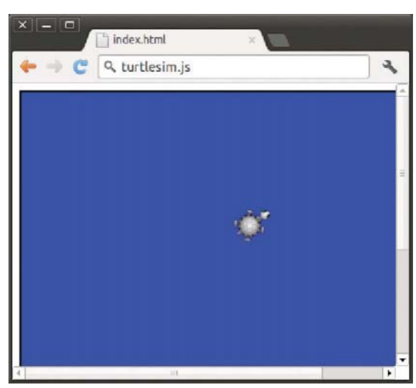


Figure 5. Tutorial interface for teleoperating a simulated turtle.

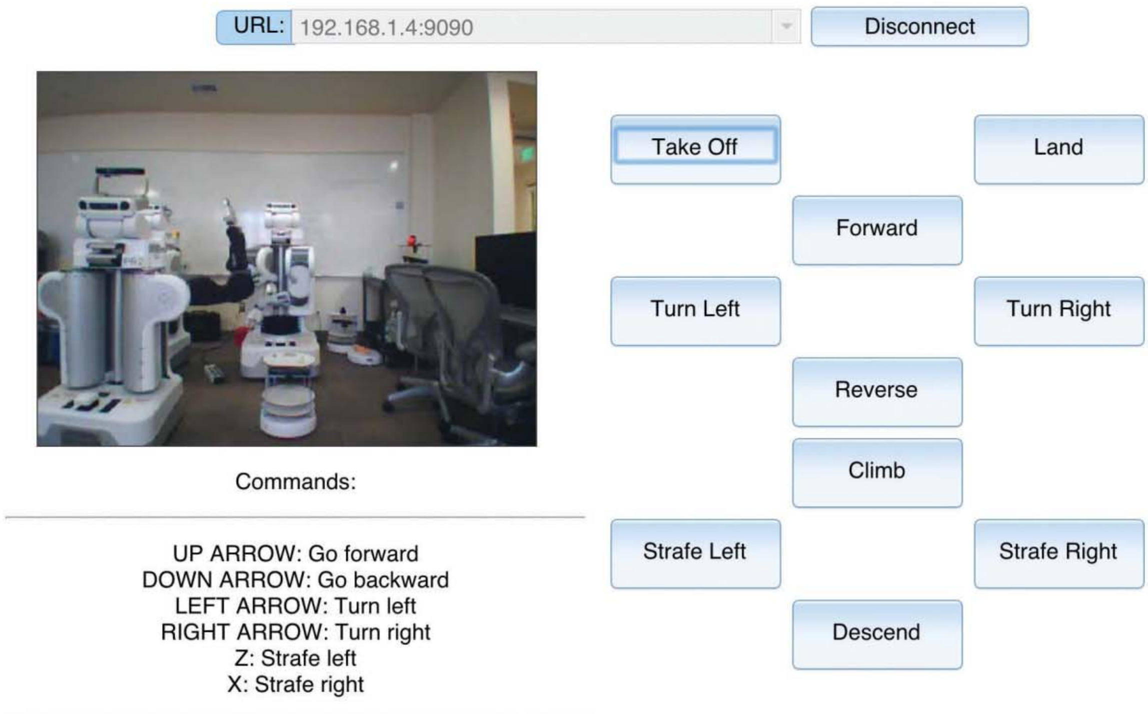


Figure 6. Tutorial interface for teleoperating a simulated turtle. Left: Tutorial interface for teleoperating an AR Drone.

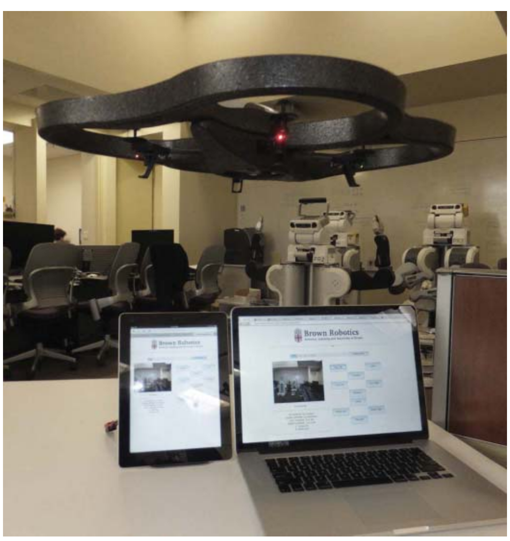


Figure 7. An AR Drone being teleoperated.

Both interfaces used the PR2 Interactive Manipulation pipeline (described in a previous ROS Topics article) as the robot backend. A Web-based implementation of interactive marker clients allowed for similar functionality in the browser as the interactive marker tools used in RViz. One of the two interfaces was made using wviz, and was customized to provide streaming camera images from the head and forearm as well as a rendered robot model with interactive markers upon launch. Additional widgets allowed the user to ask the robot to autonomously navigate using a map, and to take a camera snapshot of found objects (Figures 3 and 4).

RobotWebTools.org

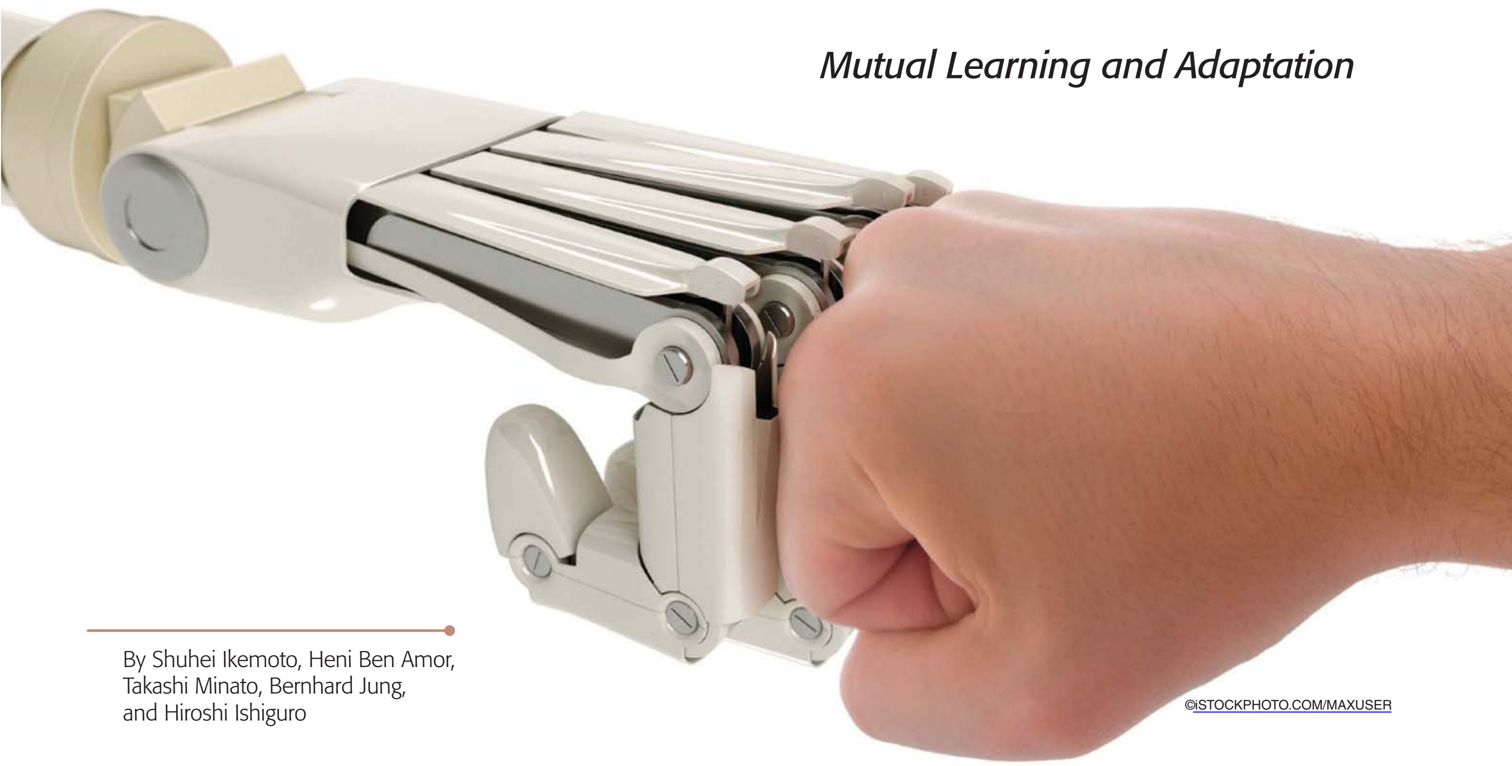
To organize the available open-source, BSD-licensed tools for robot Web applications, including those described above, and to provide support and community, a new portal wiki—Robot Web Tools—has been created at robotwebtools.org. Robot Web Tools is designed to enable Web developers, roboticists, and even students to start building a robot Web application quickly. Thus, the walk-throughs cater to all abilities, from the novice to the advanced user. Currently available tutorials include interfaces for teleoperating a simulated turtle (Figure 5) as well as a physical AR Drone (quadrotor) (Figures 6 and 7).

In addition to basic tutorials, the portal provides information on a variety of tools, libraries, and sample applications, from low-level JavaScript modules such as ros.js or 2dmap.js to full-featured robot Web applications like the Robot Management System (a Web application test platform for Human-Robot Interaction experiments). Many of the tools and projects are open sourced under the GitHub organization github.com/robotwebtools.

For those interested in joining the community of robot Web developers, information on how to join the Google Group and ongoing weekly calls is available at robotwebtools.org. And, if you create a robot Web application or tool that you would like to share, please post information about it on the Robot Web Tools wiki!

Physical Human–Robot Interaction

Mutual Learning and Adaptation



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By Shuhei Ikemoto, Heni Ben Amor, Takashi Minato, Bernhard Jung, and Hiroshi Ishiguro

Close physical interaction between robots and humans is a particularly challenging aspect of robot development. For successful interaction and cooperation, the robot must have the ability to adapt its behavior to the human counterpart. Based on our earlier work, we present and evaluate a computationally efficient machine learning algorithm that is well suited for such close-contact interaction scenarios. We show that this algorithm helps to improve the quality of the interaction between a robot and a human caregiver. To this end, we present two human-in-the-loop learning scenarios that are inspired by human parenting behavior, namely, an assisted standing-up task and an assisted walking task.

Human–Robot Interaction and Cooperation

Until recently, robotic systems mostly remained in the realm of industrial applications and academic research. However, in recent years, robotics technology has significantly matured and produced highly realistic android robots. As a result of this ongoing process, the application domains of robots have slowly expanded into domestic environments, offices, and other human-inhabited locations. In turn, interaction and cooperation between humans and robots has become an increasingly important and, at the same time, challenging aspect of robot development. Particularly challenging is the physical interaction and cooperation between humans and robots. For such interaction to be successful and meaningful, the following technical difficulties need to be addressed:

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- guaranteeing safety at all times
- ensuring that the robot reacts appropriately to the force applied by the human interaction partner
- improving the behavior of the robot using a machine learning algorithm in a physical human–robot interaction (PHRI).

In our previous research [1], we presented a PHRI scenario in which we addressed the above topics. Inspired by the parenting behavior observed in humans, a test subject was asked to physically assist a state-of-the-art robot in a standing-up task. In such a situation, both the human and the robot are required to adapt their behaviors to cooperatively complete the task. However, most machine learning scenarios to date do not address the question of how learning can be achieved for tightly coupled, physical interactions between a learning agent and a human partner. Building on the results in [2], we present an extended evaluation and discussion of such human-in-the-loop learning scenarios.

To realize learning and adaptation on the robot's side, we employ a computationally efficient learning algorithm based on a dimensional reduction technique. In particular, after each trial, the human can judge whether the interaction was successful, then the judgment is used in a machine learning algorithm to apply a dimensional reduction technique and update the behavior of the robot. As learning progresses, the robot creates a behavioral model, which implicitly includes the actions of the human counterpart.

At the same time, refining the motions of the robot during a physical interaction requires the motions of the human to be improved, because the two motions influence each other. Hence, the human counterpart is part of the learning system and overall dynamics. To analyze the efficiency of the proposed learning algorithm and the effect of human habituation to the robot during such close-contact interactions, we perform a set of PHRI experiments. In addition to the assisted standing-up interaction scenario presented in [2], we also present and discuss the first results based on a novel interaction scenario. More specifically, we present an assisted walking task in which a human caregiver must assist a humanoid robot while walking.

We believe that human-in-the-loop learning scenarios, such as that presented herein, will be particularly interesting in the future because they can help to strengthen the mutual relationship between humans and robots. Ideally, this will lead to a higher acceptance of robotic agents in society.

Related Research

Important aspects of PHRIs have been investigated in a perspective research project conducted by the European Network of Excellence (EURON) [3]. The objective of the project was to present and discuss important requirements for safe and dependable robots involved in PHRIs. Initial approaches for achieving these requirements are currently being addressed in a follow-up research project called PHRIENDS (a PHRI that is dependable and safe). To reduce risks and fatalities in industrial manufacturing workplaces, the primary goal of the PHRIENDS project is to design robots that are intrinsically safe. This requires the development of new actuator concepts, safety measures, and control algorithms, which take the presence of human subjects into account. The results of this project are also relevant to applications outside the manufacturing industry. However, learning and adaptation between humans and robots is not the focus of the PHRIENDS project.

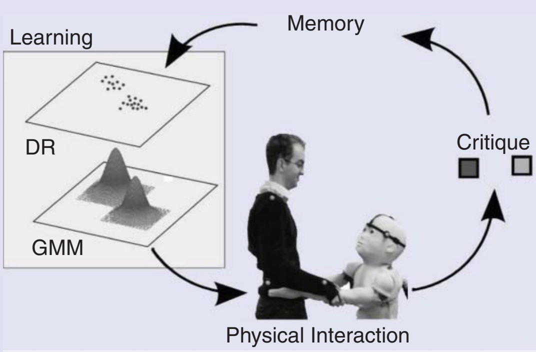
Khatib et al. [4] discussed the basic capabilities needed to enable robots to operate in human-populated environments. In particular, they discussed how mobile robots can calculate collision-free paths and manipulate surrounding objects. In their approach, they characterized free space using an elastic strip approach. However, the described robots were not expected to come into direct (physical) contact with the surrounding human subjects. The importance of direct physical interaction was highlighted in the haptic creature project [5], which investigated the role of affective touch in fostering the companionship between humans and robots. In an attempt to improve human–robot interaction, Kosuge et al. presented a robot that can dance with a human by adaptively changing the dance steps according to the force/moment applied to the robot [6]. Amor et al. [7] used kinesthetic interactions to teach new behaviors to a small humanoid robot. Furthermore, the behavior of the robot may be optimized with respect to a given criterion in simulation. In this learning scheme, the robot is a purely passive interaction partner and acts only after the learning process is complete. Similar approaches to teaching new skills have also been reported in [8] and [9] using different learning methods, i.e., continuous time-recurrent neural networks and Gaussian mixture models (GMMs), respectively. Odashima et al. [10] developed a robot that can come into direct physical contact with humans. This robot is intended for caregiving tasks such as carrying injured persons to a nearby physician. The robot can also learn new behaviors and assistive tasks by observing human experts as they perform these tasks. However, this learning does not take place during interactions but rather in offline sessions using immersive virtual environments. In [11], Evrard et al. present a humanoid robot with the ability to perform a collaborative manipulation task together with a human operator. In a teaching phase, the robot is first teleoperated using a force-feedback device. The recorded forces and positions are then used to learn a controller for the collaborative task. The main hypothesis underlying this approach is that the intentions of the human interaction partner can be guessed from haptic cues. In [12], physical interactions between a robot's hand and the hand of a human are modeled by recording their distances. The

Close physical interaction between robots and humans is a particularly challenging aspect of robot development.

Until recently, robotic systems mostly remained in the realm of industrial applications and academic research.

distances are then encoded in a hidden Markov model (HMM), which in turn is used to synthesize similar hand contacts. A recent survey on modern approaches to physical and tactile human–robot interaction can be found in [13].

In this article, we present experiments with a flexiblejoint robot that is involved in close physical interaction with a human caregiver. In contrast to the above research, both human and robot play an active role in the interaction to learn and adapt their behaviors to their partner so as to achieve a common goal. This tight coupling of robot and human learning and coadaptation is a unique feature and is the primary contribution of the present study. We assume that it is important to focus on the active role in the interaction because the forces generated during the active behavior of the robot influence the behavior of the human, which in turn influences the passive behavior of the robot. In addition, these active and passive roles cannot be clearly separated because the robot and the human influence each other when they are in physical contact.



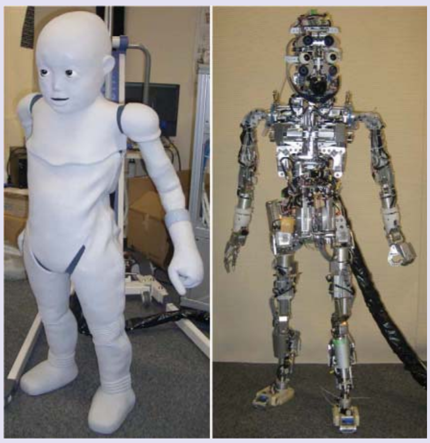


Figure 1. (a) Overview of the physical interaction learning approach. After physical interaction, the human judges whether the interaction was successful. This information is stored in the robot's memory and used for later learning. (b) Flexible-joint humanoid robot used in the experiments in this study. (Photos courtesy of ERATO Asada Project.)

Physical Interaction Learning Approach

The goal of interaction learning is to improve the cooperation of humans and robots while they are working to achieve a common goal. Figure 1 shows an overview of the learning scheme used in this article. After an initial physical interaction between a human and a robot, the human is given the chance to evaluate the behavior of the robot. More precisely, the human can judge whether the interaction was a success or failure (binary evaluation). The feedback can be provided in various ways, such as through touch or through a simple graphical user interface. Once the evaluation information is collected by the robot system, it is stored in a database in the memory. The memory collects information about recent successful interactions and manages the data for the subsequent learning step. This allows us to optimize the set of training examples used for learning to improve learning quality. Figure 1 shows the human-in-the-loop learning system considered in this article, where the behavior of the human influences the behavior of the robot and, simultaneously, the behavior of the robot influences the behavior of the human. Furthermore, the behavior of the robot changes as learning progresses, which in turn influences the behavior of the human and its physical support. This system demonstrates one of the applications of a tightly coupled physical interaction.

After a number of interactions, the learning system queries the memory for a new set of training data. The data are then projected onto a low-dimensional manifold using dimensional reduction techniques. There are three justifications for this step. First, dimensional reduction allows a reduction of the space in which learning takes place. Thus, the learning can be much faster and more efficient. In addition, dimensional reduction generally helps to detect meaningful low-dimensional structures in high-dimensional inputs. Second, dimensional reduction allows us to visualize and understand the adaptation taking place during interaction. This is particularly helpful for later review and analysis purposes. Finally, dimensional reduction reduces the negative influence of outliers on learning. The inputs to the dimensional reduction step are high-dimensional state vectors describing the postures of the robot during the interaction. The output is a low-dimensional posture space.

Once the state vectors are projected onto a low-dimensional manifold, we group the resulting points into sets according to the action performed in that state. Thus, we obtain for each possible action a set of states in which the corresponding action should be triggered. For each action, a GMM is learned. The model encodes a probability density function of the learned state vectors. The ideal number of Gaussian mixtures is estimated using the Bayesian information criterion (BIC) [14].

By computing the likelihood of a given state vector p in a GMM of action A, we can estimate how likely it is that the robot should perform action A when in posture p. The learned models are then used during the next physical interaction trial to determine the actions of the robot. Here, each new posture is projected into the low-dimensional posture space. Then, the likelihood of the projected point for each GMM is computed. Following a maximum-likelihood rationale, the action corresponding to the GMM with the highest likelihood is executed by the robot.

With each iteration of the above learning loop, the robot adapts its model more and more toward successful interactions. The result is a smoother and easier cooperative behavior between the human and the robot.

The CB² Robot

The robot used in this study is called the child–robot with biomimetic body, or CB² [15]. The robot has the following features.

- Its height is 130 cm, and its mass is approximately 33 kg.
- The degree of freedom (DOF) is 56.
- The supplied air pressure is 0.6 MPa.
- The efficient torque of the knee is theoretically 28.6 N·m.
- All joints, apart from the joints used to move the eyes and eyelids, are driven by pneumatic actuators.
- All joints, apart from the joints used to move the fingers, are equipped with potentiometers.

The joints have low mechanical impedance because of the compressibility of air. The joints can also be made to be completely passive if the system discontinues air compression during robot motion. This helps the robot to perform passive motions during physical interaction and helps to ensure the safety of the human partner. This is in contrast to most other robots, in which the joints are driven by electric motors with decelerators. The flexible actuators enable the joints to produce seemingly smooth motions, even when the input signal changes drastically. This feature of the CB² robot is used to realize complex motions using the simple control architecture [1] depicted in Figure 2. More specifically, full body motions of the robot are realized by switching between a set of successive desired postures. Furthermore, the flexible actuators enable motions generated by this simple control architecture to be adaptively changed in response to an applied force from the human partner. Each posture is described by a posture vector x, with each entry of the vector denoting the angular value of a particular joint. A low-level controller is implemented by the proportional-integral-differential (PID) control of angular values. Each time the desired posture is switched drastically, large drive torques are generated, resulting in an active force being applied to the human caregiver. As the posture of the robot approaches the desired posture, the passive motion gradually becomes the dominant motion of the robot because the amount of error in the angular control gradually becomes smaller.

The human counterpart is part of the learning system and overall dynamics.

Figure 3 shows how the examined standing-up task is realized using the proposed control architecture. The behavior is realized by switching between three desired postures. At first glance, the specifications of the robot motion appear to be extremely simple. However, the switching times are highly dependent on the human interaction. More specifically, the switching times depend on the anatomy and skills of the human. This means that the robot has to adapt the switching times to the characteristics of its partner during the period of interaction. In addition, it must be noted that this motion cannot be performed by the robot if a human does not assist in its execution.

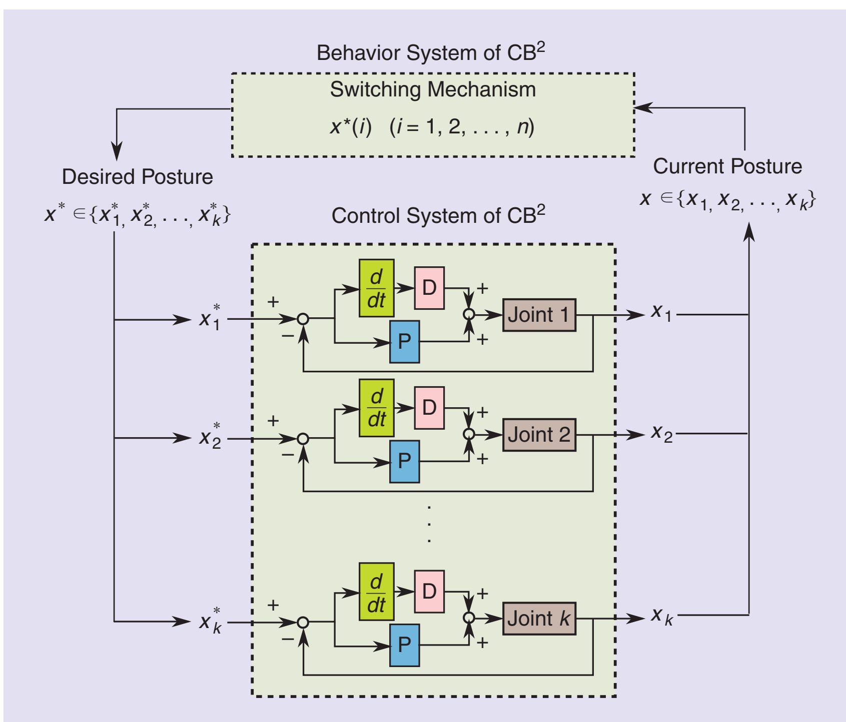


Figure 2. Control architecture of the CB² robot. The desired posture is encoded as a vector $\mathbf{x}^*$ of angular values. Using a PID controller, drive torques are generated to attain the desired posture. The switching mechanism changes between a set of different desired postures to achieve complex robot motions.

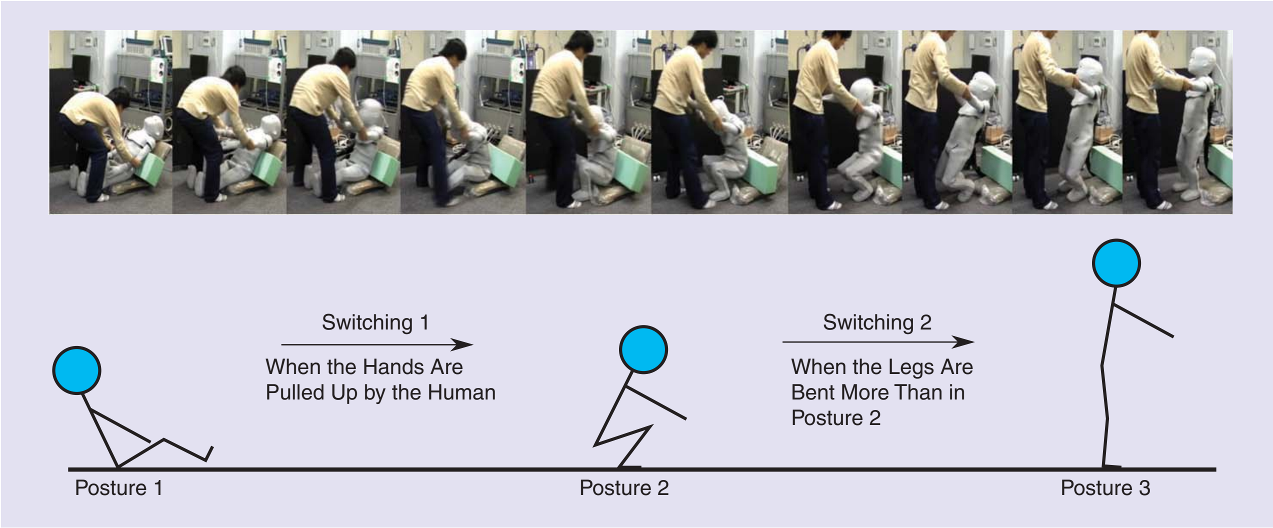


Figure 3. The three desired postures used in the standing-up task of the experiment. The learning task is to determine the ideal switching conditions between the desired postures. (Photo courtesy of ERATO Asada Project.)

Learning Method

In the standing-up task, the goal of learning is to determine the ideal timing for switching actions $x^* \in X^* \subseteq X$ between different desired postures. Here, x^* is a desired posture, X^* is a set of desired postures prepared for control, and X is a posture space that is constructed from all joint angles. This is achieved by learning three different probabilistic low-dimensional posture models: 1) for the case in which no switching occurs, 2) for the first switching action, and 3) for the second switching action.

At each time step of an interaction between the human and the robot, the realized posture and the current desired posture of the robot are recorded. The robot posture r is a 52-dimensional vector that codes the current angular value of each joint. After the interaction is complete, the postures are stored in a database in the memory. The database holds the information for the last ten interactions. Although there are several possible ways to integrate this new data into the database, the general policy used here is this new data overwrite old data, and successful interactions overwrite failed interactions.

After ten interactions, the training data from the memory are used for learning. The goal of the learning is to construct a model that indicates when the robot should switch actions by changing the current desired posture. This rule is described by a mapping from the current posture of the robot to the desired posture that the robot should use. To realize this map, we use a GMM that can construct a probabilistic model. Therefore, the objective model of the learning is a probabilistic model that indicates the likelihood of desired postures in the current state.

First, dimensional reduction is applied to the data because a 52-dimensional vector has too many dimensions to learn the model. Although a number of methods can be applied for this task, in this article, we used a principal component analysis (PCA). To perform the PCA, the mean r_{m} is subtracted from all recorded posture vectors, and the covariance matrix M of the resulting points is computed. A singular value decomposition (SVD) on M yields matrices U, V, and W, such that

$$M = UWV^T. \tag{1}$$

The columns of matrix V contain orthonormal vectors, also known as the eigenvectors or principal components (PCs), of matrix M. The matrix W is a diagonal matrix containing singular values. Each PC has a corresponding singular value that indicates how much information of the data set is covered by a specific PC. The first few PCs are then used as the axes of the lower-dimensional PCA space. Given a new data point, we can compute its coordinates in PCA space by subtracting the mean and calculating the dot product for each of the PCs.

Next, we compute a GMM for each of the three switching classes. Here, we divide the projected data points into distinct sets. If no switching occurred, then the corresponding point is assigned to the first data set. Otherwise, the corresponding point is assigned to one of the other two sets. For each set of projected points, we learn a probability density function by a weighted sum of K Gaussian distributions:

$$p(x) = \sum_{k=1}^{K} \pi_k p(x|k), \tag{2}$$

with π_k being the weight of the kth Gaussian and $p(x|k)$ being the conditional density function. The conditional density function is a d-dimensional Gaussian distribution:

$$p(x|k) = \frac{1}{\sqrt{2\pi}^d \sqrt{\det(C_k)}} e^{-\frac{1}{2}((x-\mu_k)^T C_k^{-1}(x-\mu_k))}, \tag{3}$$

with mean μ_k and covariance matrix C_k. The above $p(x|k)$ can also be written as $\mathcal{N}(x|\mu_k, C_k)$. The expectation-maximization (EM) [16] algorithm is used to estimate the parameters $\{\mu_k, C_k, \pi_k\}$ for each of the Gaussian kernels. Fortunately, performing the EM algorithm in low-dimensional spaces improves the convergence of the algorithm.

After the learning process, we end up with three GMMs coding three probability density functions, namely, $p_1(x)$, $p_2(x)$, and $p_3(x)$. In our experiments, each GMM had between five and ten Gaussians. Each probability density function can be used to determine the probability of a point in a low-dimensional posture space with respect to a particular switching action. For example, computing $p_2(r)$ for a given projected robot posture, r, returns the likelihood of the robot having to switch from the second to the third desired posture when the robot is in state r.

When the next interaction with the human starts, the robot can use the newly learned model to decide its current state and the desired posture. Here, the current joint values are projected onto the learned low-dimensional posture space. The result is a d-dimensional point. The optimal desired subsequent switching action can be computed in a maximum-likelihood fashion as follows:

$$x^*_{\text{next}} = \underset{x^* \in X^*}{\operatorname{argmax}}\, p_s(x). \tag{4}$$

In each step of the control loop, the robot calculates s_{next} and sends the angular values of the corresponding desired posture to a low-level controller. The controller then computes the needed joint torques to take on this posture. After the interaction is complete, the human evaluation information is collected and used to update the memory. The learning loop is then repeated. The above algorithm is closely related to HMMs [17]. At the same time, however, our algorithm deviates in various ways from HMM. More specifically, we do not learn the sequencing of states in our system. As a result, no explicit transition probabilities between the states are modeled.

Figure 4 shows an example of a set of interactions projected onto a low-dimensional space. Each point in the plot represents one posture of the CB^2 robot during an interaction. The points were colored according to the desired posture that was active during that particular time step.

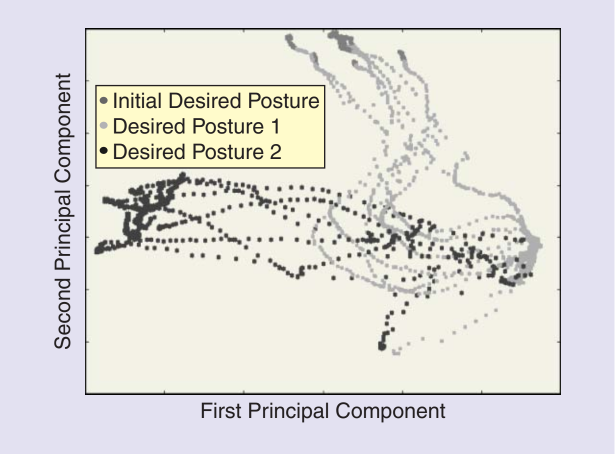


Figure 4. Interaction data for the standing-up task projected into a low-dimensional posture space. Each point corresponds to one posture of the robot.

Experiment and Results

To investigate tightly coupled adaptation and the learning scheme proposed in this article, we conducted a PHRI experiment using the interaction for the standing-up task introduced earlier. In particular, we considered the following question: "Does the learning algorithm lead to a symmetric learning process, in which both human and robot adapt their behaviors?" Furthermore, we wanted to measure the contribution of the learning algorithm to any improvement in the interaction. This required a careful experiment design that would allow us to distinguish between learning-based adaptation and adaptation due to human habituation to the robot.

The experiment was split into three independent parts. Throughout the experiment, five subjects were asked to repeatedly assist the robot in standing up. In the first part, after every ten trials, the accumulated data in the memory were used for learning a new model, according to the learning scheme described in the "Physical Interaction Learning Approach: Learning Method" section. In total, 30 interactions with two intermediate learning steps were performed. In the second part of the experiment, learning by the robot was disabled and fixed time steps were used for switching between the postures. In this baseline scenario, the only type of adaptation that was possible was the adaptation of the human to the robot. In the third and final part, learning was once again enabled (the results of the first part were not included; hence, learning started from the beginning again). The experimental design ensures that we have baseline data, allowing us to compare the results of the interactions with and without learning. In addition, by performing the baseline experiment between the learning experiments, we ensure that the user is already familiar with the robot. Thus, we rule out any distortion of the baseline result because of unfamiliarity.

To determine the ideal number of PCs on which to project the 52-dimensional posture vector of the robot, intrinsic dimensionality estimation techniques can be used [18] as a criterion. A simple estimation technique is based on the analysis of eigenvalues, which store the amount of information that is captured by each of the PCs. Hence, the eigenvalues determine how many PCs are needed to retain a specific percentage of information found in the data set. In our implementation, we automatically determine the number of PCs that capture more than 85% of the information in the data set. For our standing-up data set, this resulted in a projection onto two PCs.

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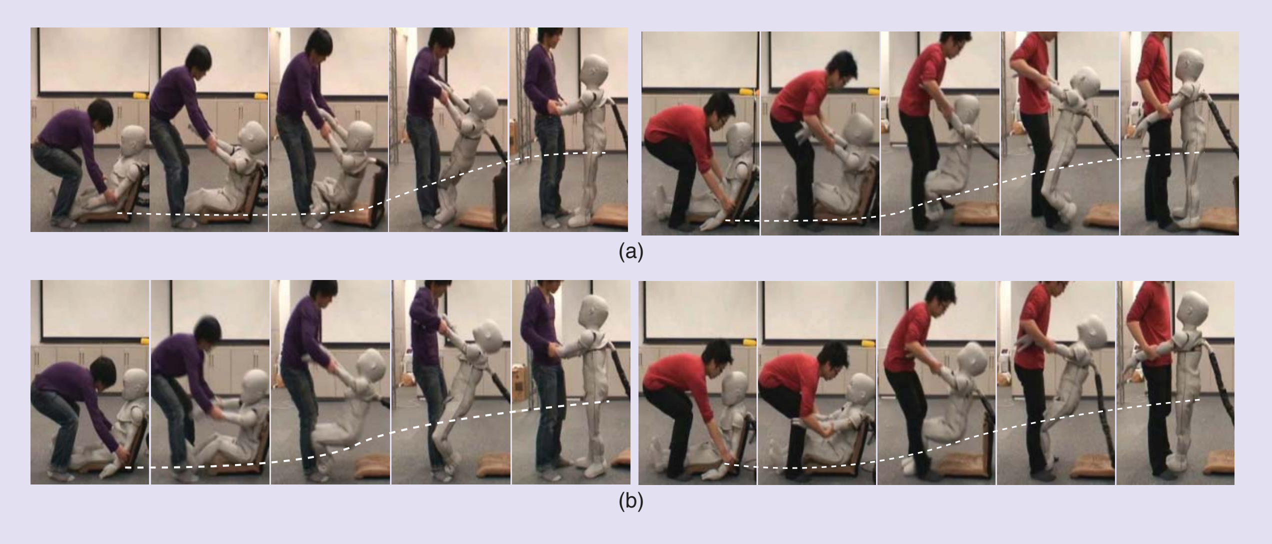

Figure 5. Sequential photographs of the (a) first and (b) last interactions of the test subjects with the robot. The white curve depicts the change in position of the robot's hips. The center photograph of each sequence shows how the robot learns to maintain firm contact between its feet and the ground for both subjects. (Photos courtesy of ERATO Asada Project.)

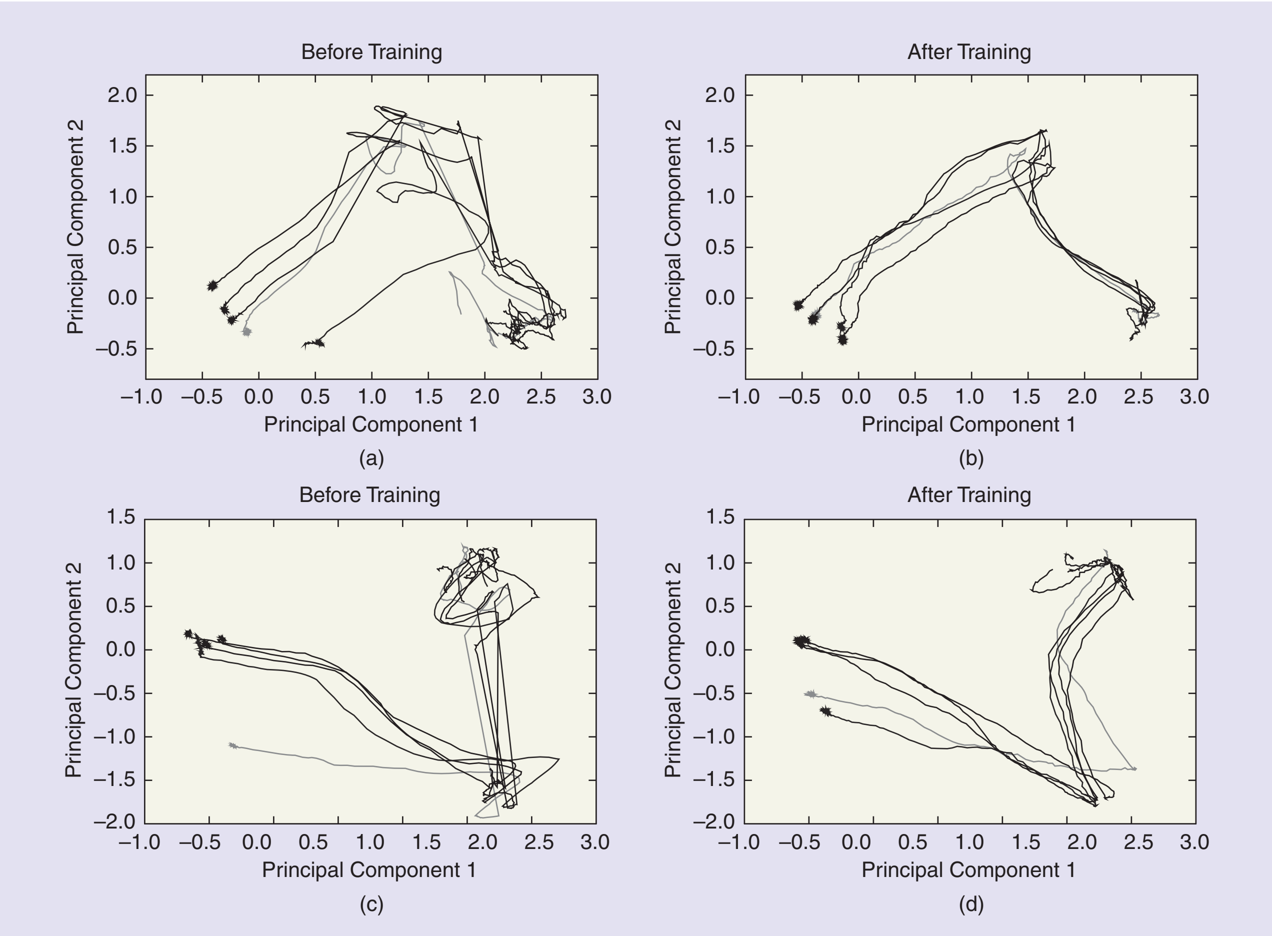

Figure 6. Projected interactions in the low-dimensional posture space: (a) and (b) the interaction trajectories for the first subject before and after learning and (c) and (d) the interaction trajectories for the second subject. In both the cases, the trajectories become smoother after learning and sudden jumps and knots are reduced. Furthermore, the trajectories become V-shaped, clearly indicating a smooth transition between the three desired postures.

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Figure 5 shows sequential photographs of the interactions of two test subjects. Figure 5(a) shows the initial interaction, whereas Figure 5(b) shows the interaction after learning. The white dashed line indicates the height of the hips in each snapshot. In the figures, we can observe a smoother transition of the hip height after the learning interaction, when compared with that before the learning interaction. In particular, the center photographs reveal strong contact between the feet and the ground and an increased hip height after learning, in contrast to the poor contact with the ungainly leg posture beforehand. Since the degree to which the human helped the robot in the task and the evaluation of the robot performance are somewhat subjective, in our evaluation, we focus only on whether the robot motion is refined to the degree that inefficient and jerky motions are avoided.

Figure 6 shows the interaction trajectories for two users before and after learning. Each trajectory was computed by projecting the robot postures into the low-dimensional posture space. Before learning, the trajectories contain loops and are partially linear. These linear pieces of the trajectories are due to jerky movements and large changes in the robot postures. In particular, for the first user, the variance in the trajectory decreases after learning. The trajectories become more similar and take on a V-shaped form. This can be explained by the fact that the interaction consists of three desired postures. Therefore, in successful trials, the interaction leads the robot from a starting posture to an intermediate posture and then to a final posture, as shown in Figure 3. In a low-dimensional space, the result is a V-shaped or triangular-shaped trajectory. This allows us to qualitatively evaluate the efficiency and naturalness of the interaction by analyzing the smoothness and shape of the low-dimensional trajectories. For example, in the case of the second subject, the trajectories before learning contain large loops at the point $(1.7, -1.5)^T$, which is the low-dimensional coordinate of the second desired posture. This phenomenon can easily be explained if we take into account our previous analysis. In the initial trials, the robot has poor contact with the floor and the legs are often not symmetrically arranged when reaching the second desired posture. As a result, lifting the robot becomes more difficult for the human and involves slight modifications of the robot posture to make the feet more stable. This interrupts the flow of the standing-up task and increases the interaction burden for the human caregiver.

To confirm the above discussion, we quantified the robot motion using the posture change norm. The posture change norm a of the robot motion was calculated using the Euclidean distance between the data of t and $t-1$ in the posture space X defined using each joint angle as a base:

$$a_{(t)} = ||x_{(t)} - x_{(t-1)}||_2, x \in X. \quad (5)$$

Computing the posture change norm at each time step of the interaction results in the time series depicted in Figure 7. The solid line shows the posture change norm during the initial interaction phase. We can see a sudden peak indicating a large change in the robot posture and, consequently, a nonsmooth motion. This is undesirable because large changes in the robot posture result from strong forces acting on the robot. The other lines show the evolution of the norm after each learning step. With each learning step, the number of peaks in the time series is reduced. In other words, the fluctuations in the posture change norm decrease, leading to a smoother and more efficient motion.

In recent years, robotics technology significantly matured and produced highly realistic android robots.

A statistical analysis of the data further underlines the above hypothesis. Here, we computed the mean and standard deviation of the summation of the posture change norm during the interactions. Figure 8 shows the evolution of these values with each learning step. For all subjects, we see that the mean and standard deviation of the posture change norm

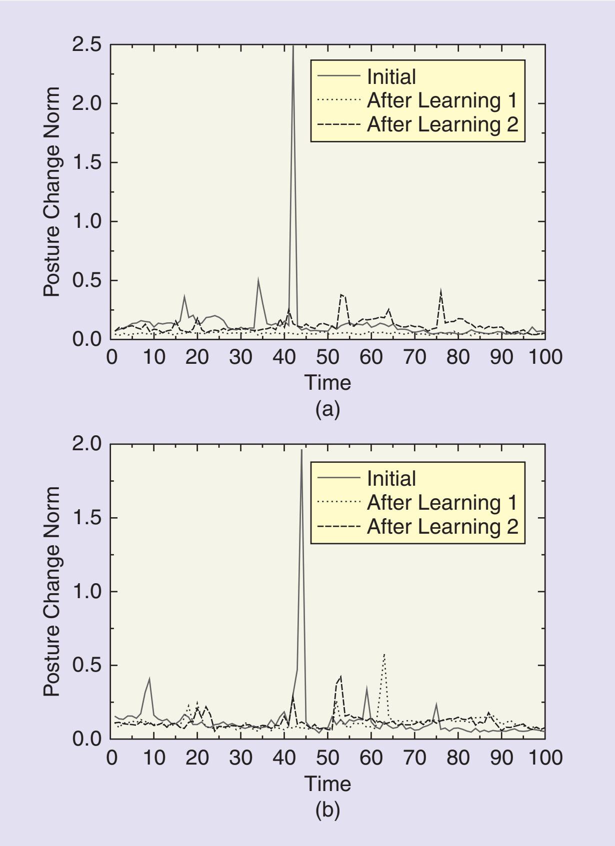

Figure 7. Evolution of the posture change norm during one learning experiment. The solid, dotted, and dashed lines show the evolution of the value when the robot has not yet learned, after the first intermediate learning step, and after the second intermediate learning step, respectively. (a) Subject 1 and (b) Subject 2.

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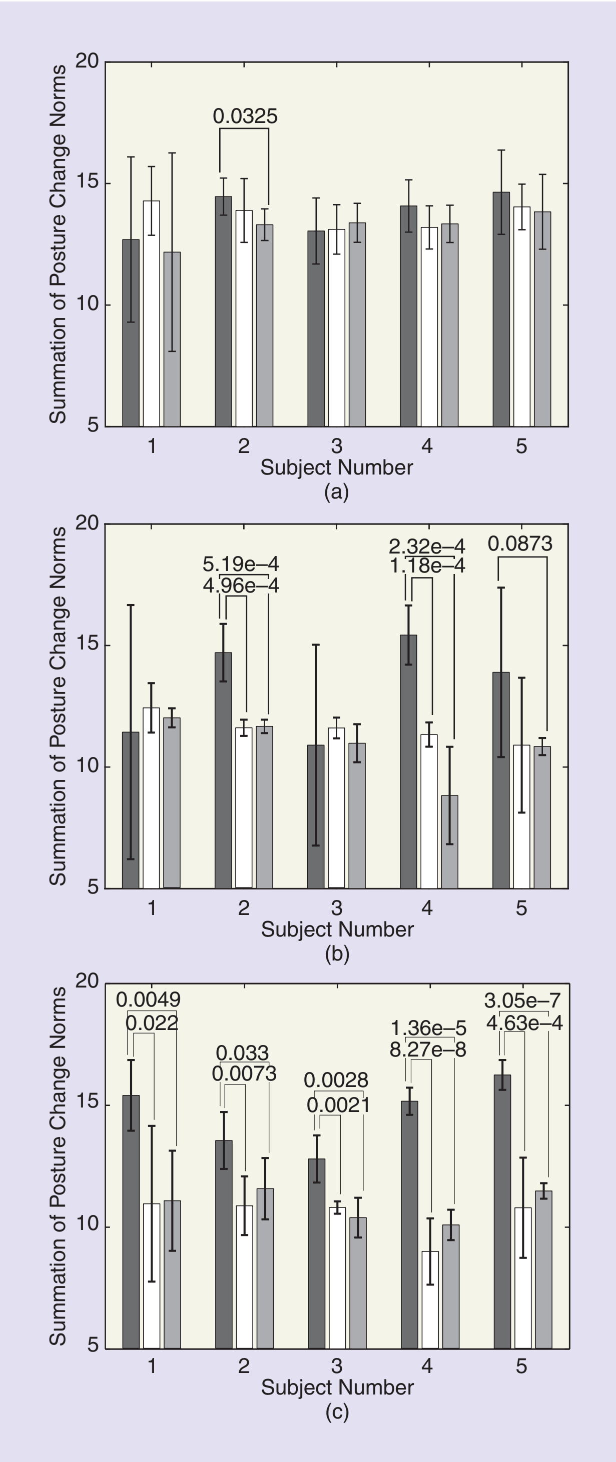

Figure 8. Mean and standard deviation of the summation of the posture change norm of test subjects in the (a) baseline, (b) first learning, and (c) final training experiments. The dark gray, white, and light gray bars indicate the mean and standard deviation values during each of the intermediate learning steps (after every ten trials). In (a), the baseline experiment, only Subject 2 shows a significant improvement after all trials. In (b) the first learning experiment, Subjects 2, 4, and 5 show significant improvements. In (c) the final experiment, the interaction with the robot improved for all subjects. With each learning trial, the indicated values decrease, and the movement of the robot becomes smoother and more synchronized with that of the subject.

decreased as the experiment progressed. In the baseline experiment, only one subject was able to significantly improve the interactions, where statistical significance is computed using a *t* test. None of the other subjects were able to improve their interactions. In the first experiment, in which the proposed learning system is used, three subjects show significant improvement. Finally, in the second learning experiment, all of the subjects showed significant improvement in their interactions. This indicates that while a human can adapt to a robot and thus improve their interactions (as in the baseline experiment), this adaptation can be significantly improved by empowering the robot with learning capabilities (first and second learning experiments). We also analyzed the maximum values of the posture change norm during the interaction. Figure 9 shows the change in the maximum posture change norm during each learning phase of the baseline experiment and the first learning experiment. No significant difference in the maximum posture change norm is observed in the baseline experiment. On the other hand, in the learning experiment, there are large changes in the maximum posture change norm. For all subjects, the values drastically decrease after learning.

Still, one possible implication from above results cannot be ruled out by the experiments performed so far. Specifically, it remains unclear how much the learning system contributes to the improvement of interaction. A possible argument would be that the observed improvements are due to the long-term habituation and experience with the robot. If this argument is true, then we should see a similar improvement of interactions as above, even if we simply repeat the baseline experiment (where learning is disabled) three times in a row. To investigate this question, we performed the aforementioned experiment (three times baseline) with all subjects. For the subjects, the experiment looked exactly the same as the other experiments: the difference was not transparent. Figure 10 compares the summation of posture change norm between the first and the third baseline experiment. In each of the experiments, only one subject made significant improvement during the intermediate learning steps. On the whole, although for some subjects slight improvement was visible (notably Subject 5), the results are not as comprehensive as when learning is enabled. This means that, while long-term habituation and experience aids the learning process, it is not sufficient for a general improvement in PHRI.

Discussion

The following observations are based on the results of the above experiments. First, when learning and adaptation were only possible on the side of the human caregiver, generally, little or no improvement could be measured. However, even in this asymmetric learning situation, at least one subject was able to adapt to the robot so as to significantly improve the interaction quality. This shows the human ability to quickly adapt to new situations and motor tasks. The second observation is that

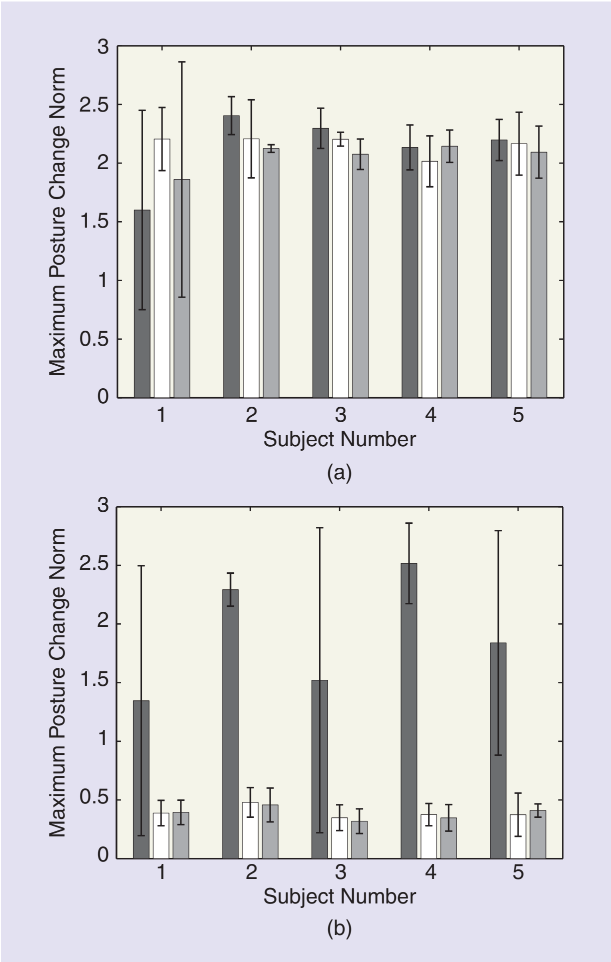

Figure 9. Change in the maximum posture change norm in each phase during (a) the baseline and (b) the first learning experiments. No significant difference in the maximum posture change norm is observed in the baseline experiment. On the other hand, there are large changes in the maximum posture change norm in the learning experiment. For all subjects, the values decrease drastically after learning.

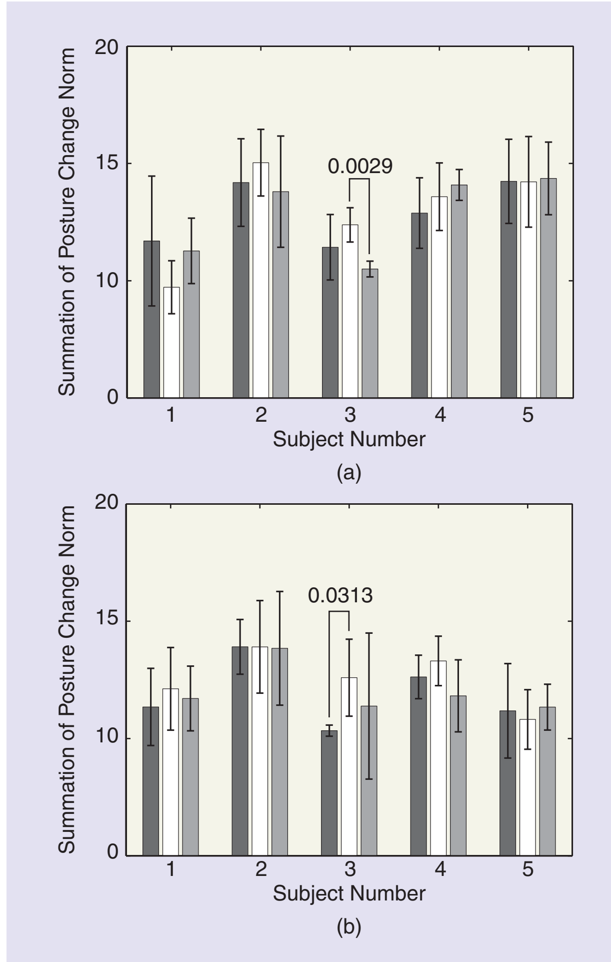

Figure 10. Baseline experiment repeated three times in a row to investigate whether improvement can be made without the robot's learning system enabled. In each of the experiments only one subject made a significant improvement. On the whole, although for some subjects slight improvement is visible (notably Subject 5), the results are not as comprehensive as when learning is enabled. (a) First baseline and (b) third baseline experiments.

the interaction quality significantly improved in the first learning experiment, and the improvement was even more remarkable during the second learning experiment. These results support our working hypothesis that the proposed learning system facilitates PHRI. Another interesting observation is that the human adaptation to the robot occurred in stages throughout the experiment. At the beginning of the experiment, the users were intimidated by the robot and the experimental setup. However, during the course of the experiment, the test subjects became more and more comfortable with the situation and the robot dynamics. As a result, the test subjects found it easier to interact with the robot. This suggests that algorithms for improving PHRI can be made more efficient if the familiarization of the human with the robot is taken into account. A special familiarization phase, in which the human caregiver becomes accustomed to the robot before any cooperative tasks, might be one approach. Another method by which to familiarize the human with the robot might be a well-designed interaction protocol that involves tasks that are intended only to familiarize the human with the robot. An interesting feature of the proposed algorithm is the ability to monitor the progress of learning as trajectories in a low-dimensional space. The results of this study indicate that the trajectories converge toward a V-shaped pattern for the standing-up task. Furthermore, the trajectories, after learning, appear to have particular points or bottlenecks through which they pass. This is reminiscent of the study by Kuniyoshi et al. [19] in which it was shown that the dynamic motions for a particular task often have a bottleneck in the state space. This bottleneck is the result of the interaction of the human body and the environment. Kuniyoshi et al. referred to this property as knack and showed that the knack can be exploited to efficiently control a humanoid robot. In the proposed PHRI scenario, the dynamics of the robot strongly depends on the dynamics of the human caregiver. A knack may be said to appear in PHRI because of the strong coupling between the

Figure 11. The assisted walking task where a human caregiver assists the robot in his or her attempt to perform several walking steps. (Photo courtesy of ERATO Asada Project.)

human and the robot and the resulting joint dynamics. In other words, the human can be regarded as a changing environment that constraints the robot dynamics. Note that, although only the posture of the robot was used to create the trajectories, we can still discern a knack that is based on joint dynamics. However, it can be argued that posture information is not sufficient enough to draw final conclusions about the joint dynamics. To address this question, we are currently investigating a different cooperative PHRI task, namely that of assisted walking as can be seen in Figure 11.

In this scenario, the human caregiver must assist the robot while the latter is trying to walk. Similar to the standing-up task, the assisted walking is realized using three desired postures: left leg up, standing, and right leg up. These postures are repeated in a predetermined order (standing → left leg up → standing → right leg up) to create a cyclic walking motion. During an interaction session, the human assists the robot in performing four cycles of the latter sequence. For a fast assessment of the applicability of our approach to different scenarios, we performed an experiment using the same setup and parameters as for the standing-up task. However, in this case, we had only one test subject performing 30 interactions with learning enabled and 30 interactions as baseline. Figure 12 shows the comparison of posture change norms between each phase (a phase consists of ten trials) in each experiment (one baseline and one learning experiment). As opposed to the baseline experiment, we can see that the posture change norms decrease when learning is enabled. Note that the baseline experiment was performed after the learning experiment to account for the human's habituation.

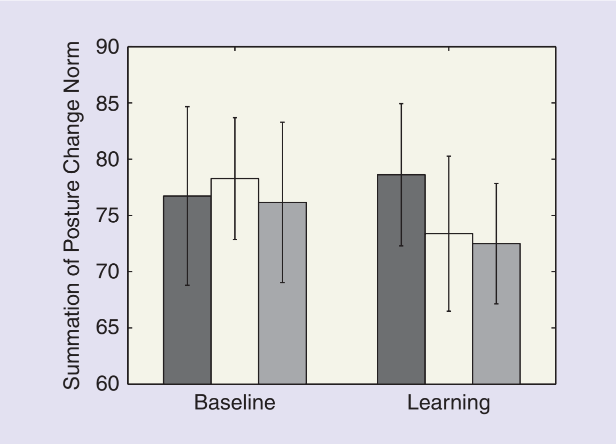

Figure 12. Summation of posture change norm for baseline and learning experiments in the assisted walking task. Each bar corresponds to a phase of ten interactions with the robot.

These early results show that the proposed human-in- the-loop learning system is not limited to the uprising interaction and that other types of interactions can be realized. At the same time, in our experiments, we found that the robot often failed to keep up when the human demonstrator drastically increased or reduced the speed of his or her walking gaits. This is due to the reactive nature of estimating the joint dynamics from the postures only. To keep up with a human interaction partner in this scenario, the robot must be more predictive in its estimation of the joint dynamics. One possible approach to overcome this problem is to include sensor information into the probabilistic low-dimensional posture models. That is, the state of the robot would be based on the current joint angles as well as the information gathered from the sensors under the skin. In this case, switching between one posture and another would also be influenced by the amount of pressure exerted by the human caregiver on the robot's body, e.g., the arms during assisted walking. Further studies are underway to obtain a conclusive answer to these questions.

Conclusions

In this article, we presented a PHRI scenario in which successful task completion can only be achieved through coordinated actions involving physical contact. We introduced a simple machine learning algorithm for adapting the behavior of the robot according to an evaluation by a human interaction partner. This method has a low computational load and can be run online during the interaction with the robot and requires relatively few training data. In contrast to previous research in this field, the robot considered in this study is in close physical contact with the human partner and plays an active role during the performance of the cooperative task. The CB^2 robot, through its flexible-joint design and soft silicone skin, is particularly well suited to such tasks because physical interactions become more natural and lifelike. In an experiment inspired by parenting behavior in humans, we were able to show that the proposed learning method results in measurable improvements of interaction. Quantitative evaluations based on the posture change norm confirm the significance of these improvements.

Thus far, the control system used herein has three parameters: the set of desired postures, the feedback gains, and the switching rule. In this article, we focused on learning the switching rule only. However, for more complex interaction scenarios it might be important to adapt all of these parameters. Another limitation of the proposed learning algorithm is the use of binary evaluation information. As a result, optimization of the parameters in a gradient descent manner is not possible. Another drawback of binary evaluation information is that only positive feedback examples are retained for use in the learning set while negative feedback examples are removed from the learning set. With respect to the first limitation, the desired postures and feedback gains can be regarded as attractors and velocities in a low-dimensional space. Amor et al. [7] have shown that such attractors can be efficiently learned in a low-dimensional space while incorporating kinesthetic assistance provided by the user. In the future, we therefore hope to integrate such a method into the proposed PHRI algorithm. As for the second limitation, we are considering the use of pressure sensors on the body of the robot. The amount of pressure issued by the caregiver can then be used as an approximate evaluation information. This allows for a finer grained reward value and, consequently, the use of modern optimization algorithms. Pressure sensors are also helpful to distinguish whether the human is currently in contact with the robot.

In summary, this study provided interesting insights into the dynamics of PHRIs. The combination of a softbody robot and an efficient learning scheme is an important step toward responsive robots that share a common living space with humans.

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Protection from Human Error

Guarded Motion Methodologies for Mobile Robots

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Industrial manipulators and unmanned systems often address a large number of tasks with some type of human-in-the-loop method. In these systems, the robot is given responsibility for some portion of the control tasks, but the human has some role for a variety of reasons; for example, the current technology may not be sufficient for the robot to complete the entire task: there may be safety, liability, or regulatory constraints, or the economics favor a human-in-the-loop process. An example of where human-in-the-loop control is of increasing interest is for telecommuting by health-care providers [1] and the general public [2] and for data gathering for disaster response [3]. These remote presence applications allow humans to perceive and act from a distance through a mobile-robot. Remote presence is more challenging than telesurgery and space telepresence from an interface perspective, as the operators are not expected to be highly trained on robots and will be working in dynamic or unpredictable environments.

To arbitrate potential conflicts between the human and robot controller, systems often implement a guarded motion functionality to integrate the competing commands. For the purposes of this article, guarded motion is defined as a method for monitoring and addressing safety constraints for human-directed operations when the human has inferior knowledge (compared to the robot) of the robot's pose and relation to its environment. In essence, guarded motion is a type of human-in-the-loop control where the robot guards itself from unintended consequences of human directives (collision avoidance, unstable configurations, excessive force, unnecessary power consumption, etc.).

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This article reviews the literature on guarded motion for mobile-robots in order to capture the state of the practice and to identify open research issues. Understanding guarded motion is important and timely because unmanned systems for remote presence applications in business, military, medicine, law enforcement, and emergency response are moving from manual teleoperation toward increased shared autonomy. These robots are becoming equipped with manipulators and are working at ever larger distances from the operator. While progress is being made in autonomy, guarded motion is also needed as an intermediate step for fully autonomous systems.

This article surveys 32 systems using a novel taxonomy created to capture both control elements (autonomy intervention criteria, command integration method, monitored condition) as well as the interface characteristics (interface modality, display preprocessing). A taxonomy for guarded motion does not appear to exist, instead the variations of guarded motion are loosely grouped together under the category of supervisory control. As Sheridan describes in [4], manual control covers methods with no autonomy, autonomous control covers methods with trivial or no human intervention, and supervisory control covers all methodologies in between. Sheridan's levels of control have been refined by the levels of automation scale presented by Parasuraman et al. in [5]. In the levels of automation classification, guarded motion systems would then occupy levels 4–7; from "[The computer] suggests one alternative" to "[The computer] executes [the suggestion] automatically, then necessarily informs the human" [5]. This framework positions guarded motion as a middle ground where human and computer generated commands must be integrated, but does not provide specific guidance on what methods to use under what conditions.

History of Guarded Motion

Because guarded motion involves both manual and autonomous control schemes, it may seem a more complex control methodology and hence something that was developed later in the evolution of robotic systems. In fact, the concept of guarded motion has been around nearly as long as researchers have been working with robots. The idea of guarded motion was first proposed by Will and Grossman in 1975 as a *guarded move*, which they define as "a move until some expected sensory event occurs" [6]. In [6], they were constructing a robot arm for automated assembly, so guarded moves were most commonly employed to allow an arm to detect when it had made contact with a surface and to stop its commanded motion path.

As with many concepts in robotics, much of the early work was done with robotic arms and other types of telemanipulators. In 1980, Bejczy presented a summary of telemanipulator work being conducted at Jet Propulsion Laboratories (JPL), California Institute of Technology, Pasadena [7]. Though he did not use the term *guarded motion*, his description of shared control systems, where ". . . the computer is in series with the operator and transforms or modulates the operator's functional commands" [7], is one of the earliest explorations of how the concept of guarded motion might be best utilized. In his work, Bejczy discusses proximity sensors being developed for the Shuttle Remote Manipulator System (SRMS), force-torque sensors, and slip sensors, and presents results that show that the shared control systems being developed decreased movement time and increased placement accuracy when compared with strict manual control. Following Bejczy, there were contributions by Lee et al. in 1985 with the JPL general bilateral manipulator control [8], Backes and Tso in 1990 [9] and Backes et al. in 1991 [10] (the first to deal explicitly with the time delays introduced by teleoperating space-based systems) with the JPL UMI telemanipulator, and Hirzinger et al. in 1993 who described the ROTEX experiment that had flown on STS-55 [11].

It is not until 1996 that guarded motion concepts (most notably both Krotkov et al. and Simmons et al.'s work on a lunar rover testbed system [12], [13]) appeared to be applied to mobile-robots. Some of the concepts originally presented in both of these early papers have evolved and are still used by the latest guarded motion developments deployed on the Mars Exploration Rover (MER), as discussed separately by Baumgartner [14], Biesiadecki and Miamone [15], Trebi-Ollennu et al. [16], and Wright et al. [17].

While some works on guarded motion, notably Krotkov et al. [12] and Simmons et al. [13], preferred the term *safeguarded teleoperation*, this article will follow the principle of priority from paleontological taxonomy, and give preference to the term first used, guarded motion, as presented in [6]. None of these sources give a clear definition of the term *safeguarded teleoperation*, but the implicit definition shows that the two terms should be viewed as functionally synonymous, or at least as referring to the same core concept.

Taxonomy

The process of examining and classifying guarded motion implementations is fundamentally a study of how the system handles conflicts (axes 1 and 2), which variables the system monitors (axis 3), and how this information is presented to the operator (axes 4 and 5). Proceeding from the definition of guarded motion posited above, a five-axis system has been devised which accounts for these questions. These axes are

1) **Autonomy Intervention Criteria:** details when the system intervenes with the commands issued by the operator.
2) **Command Integration Method:** covers how the system integrates its commands with the user's commands.
3) **Monitored Condition:** describes which variables and environmental conditions the system monitors and accounts for.
4) **Interface Modality:** accounts for how the system presents information to the operator.
5) **Display Preprocessing:** discusses how much processing is performed on sensor data before it is presented to the operator.

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Table 1. Control elements of guarded motion: autonomy intervention criteria, command integration method, and monitored condition.

	Autonomy Intervention Criteria		Command Integration Method		Monitored Condition				
System	Exception	Continuous	Traded	Blended	Obstacles	Pose	Energy	Health	Effector Force
Bologna Haptic Pioneer [18]		✓		✓	✓				
Bremen Autonomous Wheelchair [19]	✓	✓	✓	✓	✓				
CMU Pioneer [20]–[22]	✓	✓	✓	✓	✓	✓	✓	✓	
Dante II [23]	✓		✓		✓	✓			
ERA [24], [25]	✓		✓			✓			✓
ESA ROTEX [11]	✓			✓	✓	✓			✓
IBM Automated Assembler [6]	✓		✓			✓			✓
INL ATRV [26]–[28]		✓		✓	✓				
INL Packbot [29]		✓		✓	✓				
INL Pioneer [29]	✓		✓		✓				
JEMRMS-MA [24], [25]	✓		✓			✓			✓
JEMRMS-SFA [24], [25]	✓		✓			✓			✓
JPL General Bilateral Manipulator [8]	✓		✓			✓			
JPL Shared Space Telerobot [30]	✓		✓			✓			✓
JPL UMI Telerobot [9], [10]	✓		✓						✓
Lowell ATRV Jr. [31], [28]	✓			✓	✓				
MER [14]–[17]	✓		✓		✓	✓	✓	✓	
NASA 3T System [32]–[35]	✓		✓			✓			✓
NASA Ames K10 [36]	✓		✓		✓	✓	✓	✓	
NASA MESUR/Pathfinder [37]–[39]	✓		✓		✓	✓	✓	✓	
NASDA ETS-VII [40]–[42]	✓	✓	✓	✓		✓			✓
Postech pioneer [43]		✓		✓	✓				
Ratler [12], [13]	✓		✓		✓				
Robonaut [44]		✓		✓		✓			✓
Stanford Haptic Gripper [45]	✓		✓						✓
SPDM [46], [24], [25]	✓		✓			✓			✓
SRMS [33], [24]	✓		✓			✓			✓
SSRMS [24], [25]	✓		✓			✓			✓
Strathclyde ROV [47]		✓		✓	✓				
UofM NavChair [48], [49]		✓		✓	✓				
UrBot [50]	✓		✓		✓				
Wheelesley [51]	✓			✓	✓				

Table 2. Two interface components of guarded motion: modality and preprocessing.

System	Modality Count	Modality Type			Display Preprocessing		
		Visible	Audible	Tactile	Direct	Augmented	Virtual
Bologna Haptic Pioneer [18]	2			✓		✓	
Bremen Autonomous Wheelchair [19]	1			✓		✓	
CMU Pioneer [20]–[22]	3	✓	✓		✓		
Dante II [23]	1	✓					✓
ERA [24], [25]	1	✓			✓		
ESA ROTEX [11]	1	✓					✓
IBM Automated Assembler [6]	1	✓			✓		
INL ATRV [26]–[28]	2	✓		✓		✓	
INL Packbot [29]	2	✓		✓		✓	
INL Pioneer [29]	1	✓				✓	
JEMRMS-MA [24], [25]	1	✓			✓		
JEMRMS-SFA [24], [25]	1	✓			✓		
JPL General Bilateral Manipulator [8]	3	✓	✓	✓	✓		
JPL Shared Space Telerobot [30]	2	✓		✓			✓
JPL UMI Telerobot [9], [10]	2	✓		✓		✓	✓
Lowell ATRV Jr. [31], [28]	1	✓			✓		
MER [14]–[17]	1	✓					✓
NASA 3T System [32]–[35]	1	✓			✓	✓	✓
NASA Ames K10 [36]	1	✓					✓
NASA MESUR/Pathfinder [37]–[39]	1	✓					✓
NASDA ETS-VII [40]–[42]	1	✓					✓
Postech Pioneer [43]	1			✓		✓	
Ratler [12], [13]	1	✓					✓
Robonaut [44]	3	✓	✓	✓		✓	
Stanford Haptic Gripper [45]	2	✓	✓	✓		✓	
SPDM [46], [24], [25]	1	✓			✓		
SRMS [33], [24]	1	✓			✓		
SSRMS [24], [25]	1	✓			✓		
Strathclyde ROV [47]	1	✓					✓
UofM NavChair [48], [49]	1			✓		✓	
UrBot [50]	1	✓			✓		
Wheelesley [51]	1			✓	✓		

Table 1 describes the control element axes (1–3) and Table 2 presents the interface axes (4 and 5), with each table listing a range of robotic systems and noting how they are classified under this taxonomy.

Autonomy Intervention Criteria

The first of the differentiation axes, autonomy intervention criteria, describe when the system modifies the set of commands issued by the operator. The two potential values on this axis are exception and online. While the system is of course constantly monitoring in both cases, in the exception case, the system becomes fully activated if the parameter in question violates the set constraint condition, while in the online condition, the system is constantly adjusting the operator command input before it is sent to the effectors.

A common example of the exception-type intervention criteria is an emergency stop system. When the constraint is violated (the robot goes out of a GPS bounding box, it gets too close to an obstacle, or is about to enter an unsafe pose), the guarded motion behavior intervenes and stops the system to prevent it from causing any harm. Within the surveyed literature, 21 examples of exception-based intervention criteria were found. One clear example of an error condition update system, the MER, actually presents two distinct examples: the MER rover mobility and instrument deployment device (IDD) motion control software. Baumgartner [14], Biesiadecki and Maimone [15], and Wright et al. [17] all discuss different aspects of the MER mobility system, while Trebi-Ollennu et al. [16] discuss the IDD. In both cases, the system will execute a stream of commands at a given autonomy level, but if any of a myriad of safety conditions are violated, the system is halted, and operators on earth are alerted. Another example of an error condition system is presented by Griffin et al. in their discussion of a system for helping operators maintain appropriate grip force with a remote robotic hand through visual, auditory, and haptic alerts on over and under gripping conditions [45].

For online systems, the most direct example is a potential field system that is repulsed by obstacles. As an object comes closer and closer in the view of a range sensor, the system adds a proportionally increasing control vector in the direction opposite the detected obstacle. Even at longer distances where there is no danger to the robot, the system is modifying the user commands (though much less significantly) to help the operator avoid the obstacle. One example of an online system is the wheelchair with assistive navigation by Bell et al, which, in the presence of obstacles, commands the wheelchair in the unobstructed direction nearest to the direction commanded by the user and then reduces the chair's speed based on the amount of this deviation [48]. A second wheelchair by Rofer and Lankenau also uses an online methodology, but only to reduce the vehicle's speed as objects approach [19]. A final example of such an online system is presented by Diolaiti and Melchiorri [18]. Their system uses a virtual mass and spring model to apply control inputs to the rover as it approaches an obstacle.

Command Integration Method

The next axis of differentiation, command integration method, covers how the system behaves in the event of a violation of safety constraints. The systems handle this condition in one of two ways: either by assuming total control for the subsystem in question or by modifying the operator's commands to help avoid the hazard.

The logical example of traded control would be unmanned ground vehicles (UGVs) stopping during a drive action when they detect an obstacle in the directed path. Conversely, a simple example of a blended control response would be if this same UGV instead modeled the detected obstacle with a repulsive potential field and relied on the p-field methodology to appropriately divert the vehicle around the obstacle. As with the values on the autonomy intervention criteria axis, these are simply some straightforward examples, these values can be applied to vehicle mobility, manipulators, payload sensors, and across all available robot domains.

It is worth noting that traded control in this case does not fully follow the definition given by Sheridan. The given definition for traded and shared control is:

> The human may remain as a supervisor or may, from time to time, assume direct control (this is called traded control), or may act as supervisor with respect to control of some variables and direct controller with respect to other variables (shared control). [4]

Traded control in Sheridan's definition means that the human steps in and takes control for a period of time and then passes control back to the robot when they are done. In guarded motion, just the inverse of this happens. Control is still traded back and forth between man and machine, but in this case, the robot makes the decision to assume control from the operator and then relinquishes control to the human again once the given safety conditions are satisfied. The definition of blended control used here is also similar to the definition of shared control presented above, but instead of the human controlling some elements directly and the robot other elements, blended control has them both simultaneously controlling the same element and blending (through command summation or otherwise) the two sets of commands.

As previously seen with the autonomy intervention criteria, one clear example of traded control on a detected safety condition violation is the MER mobility and IDD software. In both systems, the command stream is executed until the goal condition is reached, or an error condition is reached. In the mobility software, a wide range, of conditions are monitored to make sure it is safe to drive, including sensors and vehicle health, vehicle pose, sufficient northerly tilt to maintain solar charge, time of day, and obstacles [14], [15], [17]. On the other hand, the IDD monitoring focuses on the joint sensors and the contact switch on the end of the arm (incidentally, this contact switch is also used to verify successful completion of an arm move when it makes contact in the expected position) [16]. While it could be tempting to say that simple traded control demonstrates a lower level of system sophistication or intelligence (such as when the robot is over 50 million km away), there are conditions when the absolute safety of the system is paramount, and thus the better system appears more cautious and less advanced than others. Krotkov et al. and Simmons et al. detail a similar planetary rover system in their initial development tests for a lunar rover system [12], [13]. A second example of traded control is the family of robotic arms used on the International Space Station and other spacecraft. This set of remote manipulators includes the SRMS, Space Station Remote Manipulator System (SSRMS), Special Purpose Dextrous Manipulator (SPDM), ETS-VII, Japanese Experiment Module Remote Manipulator System–Main Arm (JEMRMS-MA), Japanese Experiment Module Remote Manipulator System–Small Fine Arm (JEMRMS-SFA), ROTEX, and the European Robotic Arm (ERA). While each of these systems has a unique control system, they are all direct descendents of the original remote manipulator system, the Space Shuttle's SRMS, and all employ a traded control scheme which will stop all movement

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operations if a joint angle, force sensor, or other limitation is violated [33], [46], [24], [11], [40]–[42], [25].

On the other hand, an example of the blended control system is the assistive wheelchair navigation system presented by Bell et al.: user commands given to the wheelchair are modified with a potential field's representation of detected obstacles to drive the wheelchair in the safe direction closest to the intended user command. Similar wheelchair control methodologies can be seen in Rofer and Lankenau [19], Simpson and Levine [49], and Yanco [51], and this blended control can also be seen applied to UGVs in Bruemmer et al. [27], Goodrich et al. [52], Krotkov et al. [12], and Simmons et al. [13]. Griffin et al. illustrate a blended control system with a robotic manipulator assisting the operator in maintaining appropriate gripping force on an object [45].

Monitored Condition

The third axis, monitored condition, describes which variables and environmental conditions the system monitors and uses to reject or modify an operator directive. As noted in the definition of guarded motion,while it is tempting to constrain guarded motion simply to obstacle avoidance, guarded motion behavior can be used to monitor a much wider set of conditions than just obstacles. Unlike some of the other axes, the potential values on this axis are best represented by gradient or range of values, rather than distinct positions. In addition to obstacle avoidance, guarded motion methodologies can also be used to track vehicle pose, end-effector force, energy state and capacity, vehicle state, longitudinal system health, or any combination of these values (or numerous potential other conditions); due to space limitations, a discussion of only the most illustrative situations where the robot overrides the human is presented below.

Several examples of straightforward obstacle avoidance guarded motion have been presented in both the assistive navigation wheelchair systems as well as the UGV systems. The wheelchair systems tend to use sonar detection systems [48], [19], [49], while UGV systems see a mix between sonar, scanning laser ranger, and stereo (or other) vision systems [27]–[29], [31].

Regarding the other monitored conditions, Fong et al. demonstrate a controller that monitors not only obstacles but also pose (in the form of Euler angles to monitor for rollover) and system health (as energy state, overtemperature, motor stall, and controller failure) [20]. The other system of note for monitoring multiple data points is the MER system. The system not only watches for obstacles but also senses six degrees of freedom pose, suspension rocker bogie angles, energy state, charge capability (angle toward the sun), and system and component health (among others) [14], [15], [17].

With the early telemanipulator [8]–[10], [30], [6] and the remote manipulator systems operating in space [33], [46], [24], [11], [40]–[42], [25] it is more common for the system to monitor pose and effector force rather than monitor the overall operational envelope for obstacle avoidance.

Interface Modality

The next axis of classification, interface modality, encompasses the system interface and how the system presents information to the operator. Along this axis, systems tend to have elements from the three primary modalities (visual, audible, tactile), but they may use these elements in any of the possible combinations and permutations.

As prototypical examples, within monomodal systems, the large majority are visual systems only (as Table 2 shows, 17 visual-only systems versus zero audible-only, and four tactile-only). In simple cases, this can be only a video feed from the robot, but also includes video streams presented contemporaneously with other visual information such as numerical readouts, status messages, or video overlays. An example multimodal system might then add tactile feedback through a force-feedback controller and audible alerts to grab the operators' attention when they become intently focused on the visual display.

The field of interface design and modality is by its own right a well-established research area, readers are therefore referred to human–robot interaction (HRI) and human–computer interaction (HCI) research for numerous additional examples of monomodal, visual-based design systems (not to imply that HRI/HCI is only concerned with this type of interface, but simply that they have been well studied in this context).

However, as Table 2 indicates, monomodal interfaces are not strictly limited to the visual channel. The assistive wheelchair navigation systems already discussed all present their feedback as haptic information, either through a vibrotactile or force-feedback controller, or through changes to the chair's velocity, a haptic feedback sensed by the user's vestibular system rather than the traditional touch-based systems [48], [19], [49].

A majority of the newer UGV interfaces all discuss multimodal interfaces, either as one of the independent variables tested, or as simply the methodology chosen to develop the interface. The methods discussed include fully trimodal systems (visual, auditory, and tactile) as well as all possible bimodal configurations [27], [29], [18], [43], [53]. The robotic manipulator tests presented by Griffin et al. also evaluated the full gamut of multimodal systems with tactile, auditory, and visual alerts for gripper force [45]. This full range of possibilities is also discussed in Fong and Thorpe's survey of teleoperation interfaces (as indeed, modality applies to all such interfaces, not just guarded motion systems) [21].

Display Preprocessing

The fifth and final axis to consider, display preprocessing, is similarly concerned with how the data are presented to the operator, but from the perspective of how much and what type of processing is done to the data before they are presented to the user. The three potential values along our preprocessing axis are a direct feed, augmented reality, and virtual reality, using the most frequent occurrence of terminology from the papers themselves. As can be inferred, the direct feed simply presents the data collected by the robot directly to the user with a minimum of additional processing. *Augmented reality* then refers to a state where this basic feed has been overlaid or enhanced with additional elements of data or alternate representations of the given data. At its base, this augmented reality is still looking at the world perceived by the robot, which is in contrast to the virtual reality system where the underlying representation is a reconstruction of the environment; something not directly perceived by the robot (sensor readings are of course used in this virtual reality world, but to construct and modify the model presented to the user). We note that the boundary between augmented reality and virtual reality in older mobile-robot systems is becoming blurred, and newer mobile-robot systems may be better described as using *augmented virtuality* [54].

It should be noted that in their taxonomy of HRI, Yanco and Drury [55] identify sensor preprocessing as one of their classifiers as well. As used in the guarded motion taxonomy, we use a somewhat broader definition than the presentation in the HRI taxonomy. Yanco and Drury present two examples in their taxonomy (a sonar used to build a map, and a video with certain regions highlighted), which, in our taxonomy, would both be considered part of the middle, augmented, level, as some processing is performed on the sensor data in both cases, but the base of the display is still the direct sensor readings.

The clear example for all three of these cases is with a video stream presented to the user. In the direct-feed case, the video from the robot's camera is simply shown to the operator. The augmented reality then enhances that video stream with an overlay such as detected obstacles, navigation and goal position markers, or numerical readouts of pose, energy management, and other vehicle state information. The virtual reality interface would instead use the vehicle's detected position and relation to obstacles to construct a three-dimensional (3-D) model of the operating environment, place the robot in the environment, and then present a view of this constructed environment to the operator such that the operator is controlling the vehicle in this virtual environment, and the physical agent then is given commands to mimic the actions of its virtual counterpart.

While there are undoubtedly a large number of examples throughout the teleoperation and HRI literature, the most elementary and easiest to understand of these interface types is the direct feed. Two examples of this type are the summary of visual robotic interface elements compiled by Ellis [56], and the survey of teleoperation interfaces compiled by Fong and Thorpe [21]. Ellis discusses a broad range of elements used in many of the early visual teleoperation interfaces, while Fong and Thorpe discuss teleoperation interfaces as a whole, breaking their discussion out into direct rate controller interfaces, multimodal/multisensor systems, supervisory control, and novel controller systems.

Alternately, examples of the augmented display style can be seen in many of the UGV interfaces: particularly, clear examples are available in Fong et al. [22] and Bruemmer et al. [27].

An example of the third and final option, virtual reality is the rover sequencing and visualization program (RSVP) used by JPL to control the MER rovers. Using data collected by the stereo imagers and the HazCams on the rovers, a local 3-D model of the rover's environment is generated, and this model is then shown to the operator through RSVP. The operators then drive the rover's path for the next socially optimized learning in the virtual environment of RSVP. Based on the operator's commands to the virtual rover, a command sequence is then generated which is then fine-tuned and sent to the rover for execution. In the case of the MERs, this virtual reality capability is necessary to overcome the time delay to and from Mars; if the robot is not in a given location to take video, this view must be generated in the virtual reality space [14], [15], [17].

Such methodologies of controlling a virtual robot through a virtual environment can also be used in real time, when the video is insufficiently clear to operate from, or temporal data (such as past map elements) is difficult for operators to recall quickly and accurately [20], [27]–[29], [31]. Virtual reality can also be used not only when video is degraded but also unavailable. Lin and Kuo describe a system for operating a remotely operated vehicle (ROV) near the foundation structure of an offshore oil rig. In such a subsea environment, with high turbidity and absorptivity, insufficient light means video is not a viable sensor, except immediately in front of the vehicle where local light systems can overcome these problems. Sonar, on the other hand, can map the structure of the oil rig viewed from the ROV and then be used to register the vehicle in the water to its location to be updated within the virtual model [47].

Discussion

In addition to the taxonomy and synthesis of design heuristics, the survey of the literature provides three general observations about the history and general nature of guarded motion and identifies four open research questions for applying guarded motion to mobile-robots.

Observations

Examining the taxonomical results above, we identify three quantitative points that emerge from the evaluated literature. These observations are listed with a brief note discussing the point.

All taxonomical options had been tried at least once by 1990, except for energy and health management: Within the classifications, we looked for any natural groupings or clusters that appeared along the time axis. Rather than finding that guarded motion strategies had evolved from one type to another or that there was a clear order of development, the data revealed that, except for two particular cases, all of the potential classifications had been investigated at least once by 1990. These two outstanding cases are the energy and health-monitored conditions, which appear in the literature by 1995. Both of these conditions are particularly relevant to mobile-robot systems and systems designed for extended field service. As many of the earlier systems reviewed were either manipulator systems (where power is continuously available), or proof-of-concept vehicles designed for lab use (where it can be expected that repairs and overall system health monitoring will be performed by the researchers), it is little surprise that the first discussion of monitoring these items appears with the Mars Pathfinder mission and the Sojourner rover [37]–[39].

Obstacle avoidance, pose, and effector force are the most commonly monitored conditions: As Table I illustrates, within the surveyed literature, there were 16 examples of a guarded motion behavior being used for obstacle avoidance, 16 occurrences of it monitoring actuator/effector pose, and 14 examples where guarded motion behavior was used to monitor effector force. While there were some cases of overlap into the obstacle avoidance category (the ESA ROTEX arm [11] and the MER IDD [16] both had obstacle detection capabilities), these three common categories were primarily aligned with the type of robot: mobile systems used obstacle avoidance, while manipulators tended to monitor pose and effector force. While crossover is indeed possible, as noted above, such distinct differentiation indicates a tacit agreement by researchers on the ecological needs each type of robot encounters. Mobile-robotics typically operate in an at least partially unmodeled environment and must therefore react to objects and obstacles in the environment, while manipulator systems are typically used in a more engineered environment and are more concerned with how they interact with objects in their environment (touch or grasp an object without either slipping or crushing it).

More examples of guarded motion were found in mobile-robot systems than manipulator robots, but several examples of each exist: While not explicitly called out, Table 1 contains 20 mobile-robot systems and 13 manipulator systems that were found to employ guarded motion in fashion. While we do not claim that this table contains all systems which have ever used guarded motion, this sampling certainly shows that guarded motion can be, and has been, used on both types of robots. As the previous paragraph notes, it may be employed to monitor different conditions and perform a different function within the overall architecture, but guarded motion is still a valuable design tool for engineers constructing either types of system.

Open Research Questions

In addition to the above-noted findings, reviewing the classified guarded motion systems also raised four questions for discussion and potential future research. These discussion points are that there is no consistent method or metrics used in evaluating guarded motion systems, that visual feedback has been used almost exclusively as the primary display modality, it was unclear what the role of guarded motion would be within some of the autonomous systems currently under development, and finally, if there were conditions where guarded motion techniques would not be effective and they should not be employed. These questions will be addressed as follows:

No Consistent Methods/Metrics, Most Systems Are Proof-of-Concept

The obvious question to ask when classifying different guarded motion techniques is "which technique is best?" Discounting for the moment the fact that the answer to that question is highly task-dependent and that there, indeed, may be no distinct answer, it may be all but impossible to evaluate that question with post hoc analysis given the technique employed throughout this literature. The guarded motion systems surveyed were predominantly proof-of-concept or demonstrator systems (the exception being the fielded research platforms such as Pathfinder or MER, but these were still descriptions of systems designed to accomplish one particular task or set of tasks), and they did not employ any consistent metrics or design methods for evaluating and selecting a guarded motion methodology. Developing such a common metric for evaluating a guarded motion design or a methodology for selecting one particular design over another would be a valuable future research topic for engineers to make more informed decisions about the system as it is being designed. Considering operator/pilot situation-awareness testing as an example, while they certainly do not answer all questions, the development of situation- awareness metrics such as situation-awareness global assessment technique (SAGAT) [57] or situation-awareness rating technique (SART) [58] has allowed developers and, later, readers of the literature, to make more meaningful comparisons across systems even when there are disparities between the overall designs.

Predominance of Vision Interface

Except for the semiautonomous wheelchairs and two mobile-robots explicitly to test haptics, the primary display modality for all other systems was visual. While there were no other nonvisual systems to corroborate this conjecture, the collaborative agreement appears to be that the visual modality should be the primary interface modality, except when the operator is colocated with the robot and can directly observe the environment without computer mediation. While there appears to be no reason to contest the visual modality as the optimal channel to present guarded motion information to an operator, there also appears to be no experiments evaluating this assumption. While we would not expect the hypothesis to be rejected, we do note it as a potential area for future research.

Conditions Where Guarded Motion Does Not Work Well or Should Not Be Used

An area of significant concern is: Are there conditions where guarded motion does not work? Many of the surveyed systems included multiple levels of control, one of which was commonly a direct teleoperation interface (used for diagnostics and system checkout). While they could be controlled through direct teleoperation, or have individual actuators manipulated directly as described for Dante II [23], this was not the default operating method, but was used only under special conditions. This raises the question however: Are there any tasks or conditions where designers should not include a guarded motion type capability at all? Returning to the definition of guarded motion presented earlier, the only time guarded motion would not be useful would be when it

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was instead the robot that had inferior understanding and the human who had the superior knowledge of the robot's pose and relation to the environment. Given the known limitations of mediated perception and other detrimental factors, this is likely only a theoretical case, but nonetheless could certainly be investigated in the future.

Role of Guarded Motion in Autonomous Systems

Another question that should be raised in relation to guarded motion systems is: What is the role of guarded motion in relation to autonomous systems? Given that guarded motion was first explored in the late 1970s and early 1980s, and that there has been an increasing focus in the last decade on more fully autonomous systems, is guarded motion still a relevant technique? How does it fit in with these systems? However, Murphy and Burke [3] identify a large class of search and observation tasks, called remote presence applications, that will likely always be conducted as human-in-the-loop, and it is expected that these tasks would always benefit from a guarded motion capability. Given the presence of remote presence applications and the surprising historical pervasiveness of guarded motion seen in the section describing the history of guarded motion, it would be incorrect to assume that guarded motion is simply an old technique and will no longer be useful in the future.

Conclusion

This survey of the literature on guarded motion for mobile-robots showed that there are over 40 successful systems where the robot overrides the human directives to maintain safety, especially to avoid collisions. Given that almost every combination of intervention mechanism, command integration method, monitored conditions, interface modality, and display preprocessing were incorporated into a workable system, it was difficult to determine what works best. Instead, conclusions were divided into 1) heuristics for design that were directly supported by the studies reviewed in this article and 2) additional, more speculative design guidelines organized around the five axes in the taxonomy.

Heuristics for Design

An examination of the guarded motion systems identified in the above taxonomy yields three general findings about such systems that can help inform the incorporation of guarded motion into a robot system.

Time delay in the command loop suggested that exception-based autonomy intervention criteria be used as the control element and predictive simulation as the display element. In 1986, Sheridan clearly showed the benefits of using predictive simulation to generate operator displays when teleoperating a robot with a time delay [59]. All of the guarded motion systems surveyed that dealt with a time delay heeded Sheridan's findings and used some form of predictive simulation in their operator displays. But these time-delayed systems also had another feature in common: exception-based autonomy intervention criteria. When considering a time-delayed guarded motion system, it is understandable why exception-based autonomy intervention has been consistently selected. In a guarded motion system, autonomy intervention occurs when the operator's understanding of the robot's environment has degraded to such a degree that a safety constraint has been violated. Regardless of why this misunderstanding has occurred, the best case response will be the round-trip signal time (the return trip to alert the operator of the problem, and the outbound trip to send the correction), for any delay that is long enough to be called a delay, this is enough time for a robot to go from violating a safety constraint to causing a safety incident. To ensure safety in such a system, the robot must assume full authority when a constraint violation occurs and must allow the operators to correct their understanding of the situation so that operations can continue within the performance envelope.

Ranged exteroception is necessary for continuous autonomy intervention case. Examining the systems that used continuous autonomy intervention revealed that these systems shared a second commonality as well. All of the surveyed guarded motion systems with continuous intervention systems also employed ranged exteroceptors. This finding makes intuitive sense as well: proprioception provides binary (yes/no) indication of constraint violation, while ranged exteroception gives continuous look-ahead capability so the guarded motion system can adapt before a constraint violation occurs. Thus, we found that the surveyed guarded motion systems indicate that ranged exteroception is a necessary capability for a continuous intervention system.

Clusters of applications exist which provide *de facto* design recommendations. In examining the classified systems, we identified three consistent clusters within the available configuration space: while they did not partition the whole space, they did provide a design recommendation for the specific task that each cluster represented. The three identified tasks with clustered designs are: robot manipulators in space, rovers, and wheelchairs. For robotic manipulators in space, all of the systems surveyed (ERA [24], [25], ESA ROTEX [11], JEMRMS-MA and JEMRMS-SFA [24], [25], SPDM [46], [24], [25], SRMS [33], [24], and SSRMS [24], [25]) used an exception-type autonomy intervention criteria, a traded command integration method, monitored pose, and effector force, with a visual interface rendering a virtual representation of the robot and the task. Rovers on the other hand (such as the Pathfinder/Sojourner [37]–[39], the twin MERs [14]–[17], and the NASA Ames K10 [36]) all used exception-type autonomy intervention criteria, traded command integration, monitored obstacles, pose, energy, and system health for constraint violation, and presented the operator with a visual interface based on a virtual representation of the rover's state. While these first two systems lay somewhat close within the configuration space, the third category, semiautonomous wheelchairs, occupied a very different region of the design space (as one can imagine, the design requirements for a wheelchair and a remote scientific rover are themselves quite different). The wheelchair systems (the Bremen Autonomous Wheelchair, the University of Maryland NavChair, and Wheelesley) were

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all continuous intervention systems with blended command integration monitoring obstacles and presenting the operator information through a tactile interface based on a direct representation of the robots environment. The one exception to this wheelchair design heuristic, Wheelesley (which used an exception-type system with traded command integration), proves the rule and makes the overall point of these clustered designs. Given the strong convergence of each of these design types, future designers of such systems should consider these archetypal systems as a baseline or reference design for their systems. These systems should serve as a design inspiration but not a limitation. Future engineers should also identify where their specific design requirements diverge from the established patterns and identify how those differences should influence the guarded motion configuration they employ. Returning to the Wheelesley example, this wheelchair was designed for users with cognitive and fine motor impairments, something that had not been a requirement for the other systems. Given these additional obstacles, these users would have a significantly more difficult time to smoothly and quickly adapting their inputs based on the obstacles the chair had detected, suggesting a different type of autonomy and an alternate command integration method.

Additional Guidelines by Axis

The three heuristics captured the overall system-wide trends; however, a mobile-robot designer may construct a system as a series of design tradeoffs from within each of the five taxonomic axes in the section on taxonomy. The predictors of success for each element in the taxonomy are less clear that the three heuristics, but this section speculated on the issues and choices associated with each control or display element.

The surveyed studies showed that exception-based autonomy intervention is essential for applications with long-time delays, but the choice is less clear for applications where latency is not a problem. The choice of exception-based or continuous autonomy intervention appears to be a fundamental design decision. Is the robot fully autonomous except when an exceptional event occurs, and then control must shift back to the human, or are the robot and human continuously working together? The studies offer little insight into the answer, but continuous autonomy intervention appears attractive for applications where the human is actively involved and, is working in a complex, open environment where reaction is more important (or possible) than accurate preplanning.

Rather than choosing a single type of command integration, it may be desirable for a mobile-robot to have both traded and blended methods. The regime should always have at least one instance of traded control, where the robot overrides the human directive to perform another action, if only for an emergency stop or staying within a bounding box. Blended control, where the robot modifies or adapts human directives (such as avoids obstacles while moving in the intended direction), should be considered as the default teleoperation mode. Even if a robot calls an emergency stop and the human begins to directly control the robot, the human may not have a useful perceptual vantage point or may be encountering a significant time lag; thus the robot may be able to better sense and react to the environment.

The choice of monitored conditions for the robot to guard against depends on the task. The majority of cases where the robot took over or adapted human commands involved mobility conditions, but internal and indirect conditions are also a concern. For example, the robot might shut down rather than allow a human to burn up a motor while spinning in place. The studies surveyed in this article showed no consensus on which conditions to monitor but there was a sense that the more robust designs had a larger number of monitored external and internal conditions.

While the choice of interface modality is dependent on the specific tasks, in practice, designers have relied almost exclusively on visual displays. This practice appears to stem from convenience rather than a conscious design decision. Designers are encouraged to conduct HRI analyses to determine the division of functions between human and robot and then to apply good human–computer interface design principles so as to enable the human to realize those functions. In general, there will be at least two functions of a guarded motion interface, one is to display the nominal information needed for the nominal control regime (e.g., blended control, supervisory control) and the other is to determine why the robot has assumed control (e.g., why an emergency stop was issued). Force feedback joysticks appear appropriate for blended navigational control, and auditory or tactile alerting may be useful for signaling exceptions.

Display preprocessing is a must for human understanding of applications involving large time delays or when unusual sensors or perceptual representations are used. The appropriate amount of simulation or virtuality needed to understand why a robot has assumed control or to be confident in traded or blended control depends on the task ecology.

Summary

This article surveyed 32 manipulator and mobile-robot systems that rely on guarded motion. Guarded motion provides a methodology for the robot to track and monitor safety conditions it is better suited to observe and then integrate its findings with the command sequence provided by the human operator. It has been used in some form since 1975 and will likely play an important role in future systems for military, medicine, law enforcement, and emergency response applications as they shift from teleoperation to increased autonomy, where the advances in autonomy are not sufficient or mission, safety, regulatory, or economic concerns require human participation. To classify and analyze the surveyed systems, a novel five-axis taxonomy for guarded motion was created. The axes are autonomy intervention criteria, command integration method, interface modality, display preprocessing, and monitored condition. These differentiators cover when and how the system intervenes, how this information is presented to the operator, and finally, what conditions are monitored by the system. The taxonomy is expected to be capable of accounting for all of the systemic differentiations between any future guarded motion implementations and serves as formal basis for comparing designs. The article also contributed a set of design heuristics on what control and display elements to use for certain conditions and identified several open research questions. The survey, taxonomy, heuristics, and discussion are expected not only to add to the fundamental theory of autonomy and HRI but also serve as a practical guide to implementing a guarded motion system.

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Domestic and industrial robots, intelligent software agents, virtual-world avatars, and other artificial entities are being created and deployed in our society for various routine and hazardous tasks, as well as for entertainment and companionship. Over the past ten years or so, primarily in response to the growing security threats and financial fraud, it has become necessary to accurately authenticate the identities of human beings using biometrics. For similar reasons, it may become essential to determine the identities of nonbiological entities. Trust and security issues associated with the large-scale deployment of military soldier-robots [55], robot museum guides [22], software office assistants [24], humanlike biped robots [67], office robots [5], domestic and industrial androids [93], [76], bots [85], robots with humanlike faces [60], virtual-world avatars [109], and thousands of other man-made entities require the development of methods for a decentralized, affordable, automatic, fast, secure, reliable, and accurate means of authenticating these artificial agents. The approach has to be decentralized to allow authority-free authentication important for open-source and collaborative societies. To address these concerns, we proposed [117], [120], [119], [38] the concept of *artimetrics*—a field of study that identifies, classifies, and authenticates robots, software, and virtual reality agents. In this article, unless otherwise qualified, the term *robot* refers to both embodied robots (industrial, mobile, tele, personal, military, and service) and virtual robots or avatars, focusing specifically on those that have a human morphology.

Virtual worlds populated by software robots are an area of particular concern [123]. A quick investigation of the Second Life virtual world shows that it is populated by organizations posing security

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Artimetrics

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risks, including international terrorist groups and local groups of radicals. Virtual worlds can be used to create an exact replica of a real-world target and can be utilized to rehearse an entire attack online, including monitoring the response and ramifications [78]. We can further illustrate the problem by analyzing the examples of news reports about the crimes reported to be committed in the virtual communities. These crimes are either committed by members of the virtual communities through their avatars or directly by creating malicious software that can accomplish committing the crime. In either case, "as in the real world, one of the central difficulties is establishing the identity of individuals" [79]. The examples given below are by no means exhaustive, because almost any type of real crime has a virtual equivalent [123]

1) *Theft of Virtual Property*—"The Netherlands teen sentenced for stealing virtual goods" [33]
2) *Virtual Prostitution, Strip Clubs, and Pornography*—"Escorts, the Second Life equivalent of phone-sex operators or prostitutes, are quite common in Second Life" [115]
3) *Virtual Gambling*—"FBI checks gambling in Second Life virtual world" [84]
4) *Virtual Money Laundering*—"Second Life and other online sites targeted by criminals" [105]
5) *Virtual Fraud*—"…the 'bank' vanished, and depositors say their money did, too" [106]
6) *Identity Theft*—"Second Life charges for real names, increases identity theft risk" [113]
7) *Illegal Content (Child Porn)*—"Second Life 'child abuse' claim" [9].

In addition to numerous examples of virtual crime, it is also interesting to look at other scenarios in which it would be useful to track an individual between the real and virtual worlds. For example, a number of cases have been reported in which a wanted criminal is easily found in the virtual world and even taunts authorities by posting status updates and pictures of his real environment [97], [111].

In the context of investigating criminal and terrorist activity outlined above, we see six (four nonsymmetrical) scenarios requiring an automated matching algorithm (see Figure 1). For each scenario, we have provided a realistic example meant to motivate the need for a particular matching algorithm [123].

1) *Matching a human face to an avatar face and vice versa* [Figure 1(a)]: This capability is useful to connect a person's real identity to their virtual persona. It is increasingly common to upload a real photograph to serve as a prototype for a 3-D avatar, as well as to create drawings closely resembling the actual person to serve as the online persona.

   Example scenario 1 (avatar to human): During a forensic investigation of a personal computer, a number of images depicting virtual pornography are found. It is desirable to run the virtual faces against the database or real-life sex offenders to see whether any quality matches can be detected for further investigation.

   Example scenario 2 (human to avatar): To follow up a convicted sex offender forbidden from interactions with anyone under 18, it might be valuable to do a visual search of virtual playgrounds to see whether the person is violating the court order in cyberspace.

2) *Matching the face of one avatar to another avatar* [Figure 1(b)]: This capability is useful for continuously tracking a virtual persona through cyberspace at different times and in different places.

   Example scenario 1: An intelligence agency might be interested in automatically tracking a suspected terrorist across the virtual community for many days to establish his contacts and frequently visited places.

   Example scenario 2: The same capability might be extremely useful in personalization and customization of services, for example, to load certain user preferences if a recognized avatar returns to a previously visited business.

   Example scenario 3: The ability to recognize avatars and profile them on the basis of appearance is also very useful in marketing; for example, a cosmetics company selling their product in a virtual world might be interested in advertising to all female avatars who appear to use a lot of lipstick.

3) *Matching an avatar's face from one virtual world to the same avatar represented in a different virtual world(s)* [Figure 1(c)]: A recent development in the world of virtual communities is the desire to interconnect different virtual worlds. "One such world, called HiPiHi, is being created in China. HiPiHi founders said they want to create ways for avatars to travel freely between its virtual world, Second Life and other systems—a development that intelligence officials say make it doubly hard to track down the identity of avatars" [79].

   Example scenario: A well-known criminal has set up recruitment camps in multiple virtual worlds (Second Life, Entropia Universe, etc.). To fully understand his minute-by-minute activity, network of contacts, and overall strategy, it is necessary to track him beyond a single virtual world to all corners of the cyberspace. Because the same real-world photograph will be translated to slightly different-looking avatars depending on the algorithm used by a specific virtual world, it is very

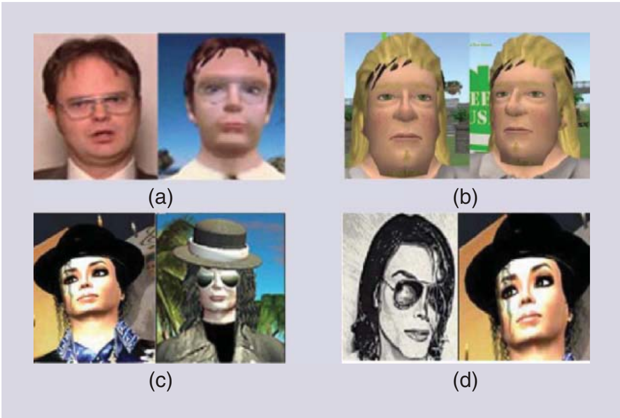

Figure 1. Four possible avatar-matching scenarios useful in forensic investigations [123]. Images from (a) cyberextruder.com, (b) SecondLife.com, (c) SecondLife.com and EntropiaUniverse.com, and (d) RedFieldPlugins.com.

valuable to do intervirtual world avatar tracking via avatar-to-avatar matching.

4) *Matching a sketch of an avatar to an avatar's face and vice versa* [Figure 1(d)]: Because it is useful to match a sketch created on the basis of the description provided by a victim or a witness of a crime to a picture of a criminal from an FBI database, it is also important to match a sketch of a virtual criminal to an actual avatar responsible for the crime.

   Example scenario 1 (sketch to avatar): In the case of a virtual crime [68], the victim may not know the identity of the avatar responsible but will probably provide a verbal description of the assailant from which a sketch artist will generate a fairly close representation of the wanted avatar. Given such a sketch, it is desirable to have the technological ability to scan through a dataset of avatars in the given virtual community and find avatars, which are best matches for the sketch.

   Example scenario 2 (avatar to sketch): In a scenario similar to the one above, if a database of all the avatars in the world is not available, a wanted poster approach might be utilized. In this approach, a sketch of the wanted criminal is made public in the virtual world, and avatars passing by can compare their acquaintances to the depiction on the wanted poster.

With continued progress in software and hardware robotics and related fields, it is logical to expect the next generation of robots to resemble humans and possess the abilities of humans, including walking, speaking, typing, and making decisions (Figure 2 shows how robots are becoming more humanlike with every generation).

It is also likely that robot owners might choose to customize their robots' appearances, similar to people frequently electing to customize their cell phones or computers via "skins" or desktop wallpapers, which will result in robots being truly unique in appearance. The feature that naturally lends itself to customization is the face; in fact, celebrity look-alike [80] and model robots [47] have already appeared. The robots of tomorrow may also present a security threat to people, property, and cyber infrastructure, depending on who is controlling them and their learned skills. Thus it is a natural progression to extend research in biometrics-based human authentication to methods for recognition of robots.

Biometric authentication is applicable to intelligent robots/software authentication in a number of different instances. Lyons et al. discussed specific steps and processing techniques needed for an avatar to be created almost automatically from the human face [69]. In fact, the process described by Lyons et al. is essentially the process of biometric synthesis [126]. Users of virtual worlds have also noted that avatars very often resemble the characteristics of its creator, not only in facial characteristics but also in body shape, accessories, and clothes.

But what about other less obvious resemblances such as manner of communication, response to various situations, nature of work, leisure/recreational activities, and time of appearing in the virtual world? All of the above encompass behavioral characteristics or soft biometrics [49] that can be exploited by fusing biometric-based techniques with methodology tailored to the specifics of virtual world. Such behavioral characteristics are even less likely to change than the avatar's facial appearance and clothes during the virtual world sessions, as users typically invest a lot of time and money into the creation of a consistent virtual image and are unlikely to change an avatar's patterns of behavior.

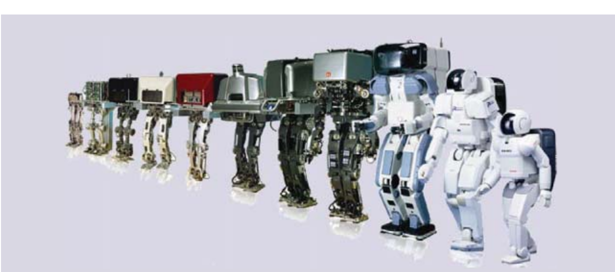

Figure 2. Evolution of the Honda Asimo robot from 1986 to 2000 [46].

Literature Review

To date, very few works have dealt with the visual or behavioral authentication of robots. The need for the development of robotic biometrics has been identified in [127]. Relevant work has been done in program recognition [83] and program understanding [87] in which the source code of a program is analyzed with the goal of understanding the original purpose behind the creation of such software. Others have researched robot behavior recognition and prediction, never applying the discovered trends to the recognition of robots exhibiting the observed behavior [7], [44]. Finally, work in robot detection [54], [108] and robot self-recognition [53], [40] is closely related and can serve as additional support for the proposed research.

Although no research has been reported in automatic robot authentication or behavior analysis, some relevant research has been published on robot emotion recognition [34]. Canamero and Fredslund conducted a study to evaluate how accurately humans can recognize facial expressions displayed by the humanoid robot Felix. The average recognition accuracy of emotion expressions was 58% for adults and 64% for children. In a control group recognizing emotion in human faces, the results were 82% for adults and 70% for children [18]. The surprising conclusion of this study was that children are better than adults at recognizing robots' emotional states, which could possibly be explained by children's significant exposure to modern cartoons populated by robotic creatures.

In a different set of experiments, Elliot tested the ability of intelligent agents to express emotions by having humans gather enough information from the agents' different communication modalities to correctly assign intended meanings to ambiguous sentences. These agents can interact with subjects using speech recognition, text-to-speech, real-time morphed schematic faces, and music. By comparing the performances of computerized agents to human actors, Elliot showed that artificial agents outperformed humans by 53–70% [32]. In a related set of experiments, Bruce et al. determined the degree to which emotional expression affects a robot's ability to

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engage with humans [17]. Their robot exhibited different emotions on the basis of its success at recruiting a passerby to take a poll. The results showed that having an expressive face and appropriate movement (body language) increases a robot's chance of successful interactions.

The work of Delaunay et al. [31] focused on understanding how a person in a human-robot interaction can read gaze direction from a robot. Results of their experiments indicate that although it is hard to recreate human-human interaction performance, robot faces having a humanlike physiognomy perform equally well, which seems to suggest that these are the preferred candidates to implement joint attention in human-robot interaction [31]. Saerbeck and Bartneck [92] analyzed the relationship between the motion of a robot and perceived effect on human beings. Acceleration and curvature appear to be the most influential factors in how the motion is perceived. Experimental results suggest a strong relationship between motion parameters and attribution of affect, while the type of embodiment had no effect.

Riek et al. [90] showed that people cooperate with abrupt gestures quicker than with smooth gestures. A person's speed at decoding robot gestures is correlated with his or her ability to decode human gestures, and negative attitudes toward robots are strongly correlated with a decreased ability in decoding human gestures [90]. Chaminade et al. [21] gave instructions to volunteers to explicitly attend to the emotion shown by human and robot subjects. A significant increase was observed in response to robot, but not human facial expressions in the anterior part of the left inferior frontal gyrus, a neural marker of motor resonance [21].

The research on robots exhibiting emotions has a rich history. The following is a short list of robots that demonstrate different levels of facial expressions [18].

Affective Tiger is a toy robot developed as a tool for social and emotional awareness education of young children. Tiger's face has two degrees of freedom (2 DoF) (mouth and eyes) [57].

Minerva is an interactive tour guide robot that displays four emotions: neutral, happy, sad, and angry. It has 4 DoF: two for mouth control and two for the eyebrows [23].

Sparky is a teleoperated robot, which uses facial expressions, gestures, motions, and sounds to interact with people. His face has 4 DoF to control three expressive features—eyebrows, eyelids, and lips [98].

Kismet is a famous MIT robot developed as a testbed for learning social interactions between robots and people. Kismet's face has 18 DoF that allow the robot to express a full range of emotions, which have been shown to be correctly interpreted by people [16].

iCub was designed by a consortium of European institutions to simulate the perceptual system and articulation of a small child and to interact with the world in the same way that a child does. The robot has 53 DoF distributed between its arms (seven each), hands (nine each), head (six), torso (three), and legs (six each) [77].

In addition to experiments on understanding the emotional states of robots, some work has been started on the general analysis of avatar behavior [15]. Another novel research direction is known as Avatar DNA, a patent-pending technology from Raytheon [110]. A recently published article demonstrates the feasibility of applying strategy-based purely behavioral biometrics developed for the recognition of human beings to the recognition of intelligent software agents [122]. The article lays the theoretical groundwork for research in the authentication of nonbiological entities. Specifically, it is demonstrated that behavioral biometrics is a sound approach to intelligent robot authentication.

Artimetrics

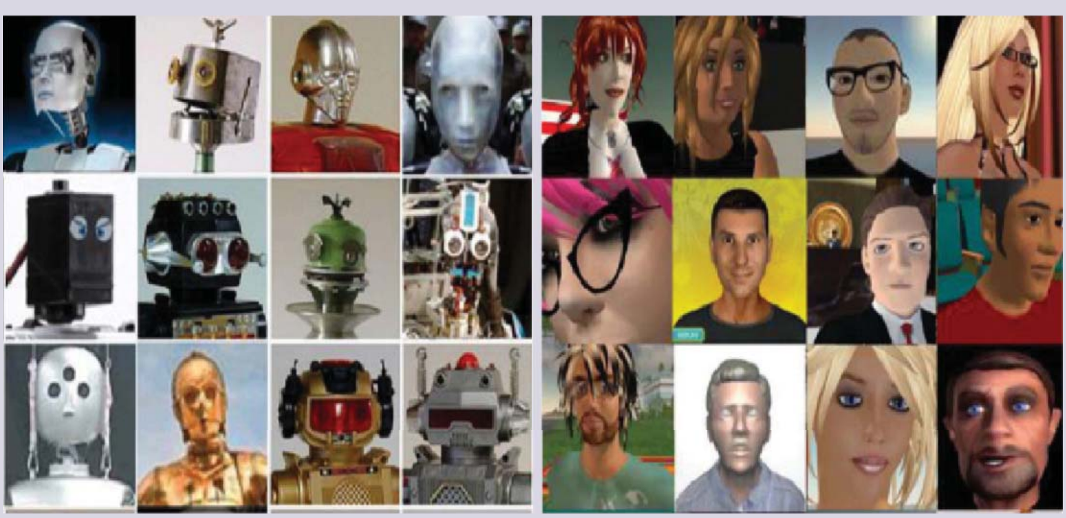
Database Generation and Availability

In well-established fields such as biometrics, numerous standardized and publicly available datasets exist [66], making it possible to compare different algorithms and to test developed systems. Labeled public datasets of robot faces, avatars, or attributed conversations from artificially intelligent agents are currently unavailable. A visual survey of robots [38] contains images of various artificial entities but not a standardized database suitable for subsequent research. Methods for synthetic iris, face, and fingerprint database generation for biometric research were recently surveyed [119], [120]. However, for the robot domain, this is mainly an unexplored area of research. Techniques for the creation of such standardized datasets that are consistent with real-world datasets can be imitated by examining the approaches to the generation and evaluation of facial datasets [59], [37] utilized by biometric systems or from chat mining research applied to gender attribution and human versus bot classification [27], [39].

The authors have begun to work on the generation of a publicly available avatar face dataset [82], and on the collection of speech corpora from intelligent agents—two types of data, which are of specific interest in the early artimetrics research. One database consists of a set of high-resolution facial images of avatars collected from two of the most popular virtual worlds: SecondLife.com and EntropiaUniverse.com. The other database consists of a text corpus from intelligent agents who have performed extremely well in the recent Loebner Prize in Artificial Intelligence (AI) competitions (Loebner.net). We have developed automated tools utilizing the power of AutoItScript.com and the Linden scripting language (LindenLab.com) for the creation of customized datasets of both kinds. With the assistance of the developed tools, researchers in the field can effortlessly generate virtually unlimited amount of data for visual and stylometric robot authentication experiments. Additional work is still necessary to make it possible to generate data with specific characteristics. Currently, it is only possible to specify the desired amount of data, the gender of the avatars' faces, and the overall area of knowledge over which the intelligent agents communicate. It is, however, already possible to generate multiple samples for each nonbiological entity, making it easy to perform training and testing on disjoint datasets. In parallel, we are working on assembling a dataset of hardware robots' faces, a process which, due to the current limited number of such robots, is done manually and provides limited control over such factors as DoF in facial expressions (see Figure 3). First evaluation results on such synthetic databases have appeared in the literature [130], [118], [13], [3], and the achieved accuracy rates are comparable to those achieved on human face datasets. The difficulties faced by artimetrics researchers are similar to those in the field of biometrics, such as chaotic and noisy environments, varied lighting conditions, subject occlusion, and system spoofing by well-trained adversaries.

Visual Artimetrics

1) *Goals:* Authentication of robots can be carried out through some methodologies developed for authenticating human beings in the field of biometrics and in others dealing with the attribution of identity, such as authorship recognition or stylometry (as practiced in forensic science). Biometrics is defined as the science of human identity authentication via analysis of measurable physiological and behavioral characteristics [49], [50]. With respect to authentication, face recognition is one of the most popular physical biometrics, which can also be applied to authentication of humanoid robots. Prior research related to *visual authentication* of identity on the basis of face analysis that can be applied to robot authentication is summarized below.
2) *Methods:* Face detection is the first step in the authentication process in which a face is located in an image to make further processing possible. A very large number of articles have been published on the topic; interested readers are referred to survey articles [125], [129], [107] as well as a recent book [48] on facial biometrics. Dozens of different approaches ranging in accuracy from 60% to 99% have been proposed [125]. They are generally classified as knowledge-based, feature-invariant, template-matching, and appearance-based. Knowledge-based methods, such as the multiresolution-based approach [124], capture the relationship between facial features. Feature-invariant approaches look for the structure's consistency under a variety of poses and lighting conditions; examples include grouping of edges [128], a space gray-level dependence matrix [30], and a mixture of Gaussians [70]. The template-matching method extracts standard patterns of the face, which are later compared to regions being tested to determine the degree of correlation; classical examples include a shape template [29] and active shape model [64]. Finally, appearance-based methods, such as Eigenvector decomposition [112], support vector machines (SVMs) [81], the hidden Markov model [89], the naive Bayes classifier [99], and neural networks [91] learn facial templates from a set of training images.
3) *Pros and Cons:* Among listed methods, approaches such as appearance-based became highly popular because of their resistance to changes in lightning conditions, distance from camera, sensor devices, and orientation. Template-matching methods exhibited great performance on databases with less variability and predicted image elements; they, however, perform poorly on cluttered, obstructed, or low-quality images. Feature-invariant methods or geometric approaches are popular due to their simplicity and fast recognition rates, but presently they are usually augmented with appearance-based methods or template-based methods. Knowledge-based methods were the earliest developed methods and now they are rarely used.
4) *Current Directions:* The first successful attempt to apply a neural-network-based learning system for synthetic fingerprint recognition has been reported in [1]. There are also combined approaches becoming more and more popular with multimodal biometric systems being developed on the basis of a high-dimensional vector representing the



(a) (b)

Figure 3. (a) Sample images for a robot face dataset, currently limited to manual collection. (b) Automatically generated random avatar faces [120], [82].

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combination of features extracted by variety of the above methods [41]. Recent state-of-the-art research on such complex systems utilizes information fusion for decision making and learning approaches from the AI domain [37].

An important biometric problem is face identification. Holistic methods use the whole face as the input to the recognizer and rely on principal component analysis (PCA) and its variants, such as Eigenfaces [28], Fisherfaces [10], SVM [86], and independent component analysis [8] to perform identification. Feature-based methods work by extracting structural features such as location of the eyes and lips from the image, and that data serve as the input to the classifier, which uses hidden Markov model [96], convolution neural network [65], or graph-matching [116] algorithms to achieve facial pattern identification.

The first results in this area appeared in a 2010 paper [123], coauthored by A. Jain, which introduced concepts of verification and identification of avatar faces. Recent 2011–2012 papers [118], [3], [13], [73], [74] and [130] reported the first numerical results validating approaches on an avatar face database. At the same time, research on behavior artimetrics has commenced.

Behavioral Artimetrics

1) *Goals*: Forensics, and more specifically authorship recognition (sometimes called "stylometry"), is one of the sources of prior research related to behavior-based authentication of identity.
2) *Methods:* In particular, a lot of research has been done in vocabulary analysis and profiling of plain text [52], [62], [63], e-mails [104], [114], and source code [101], [42], [35]. Written text or spoken language, once transcribed, can be analyzed in terms of vocabulary and style to determine its authorship. To do so, a linguistic profile needs to be established. Many linguistic features can be profiled, such as lexical patterns, syntax, semantics, pragmatics, information content, and item distribution through a text [43]. Commonly utilized text descriptors include word count, punctuation mark count, noun phrase count, word included in noun phrase count, prepositional phrase count, word included in prepositional phrase count, and keyword count [102]. Once linguistic features have been established, SVMs [51], Bayesian classifiers [58], multiple regression, and discriminant analysis [103] algorithms (among others) have been applied to determine the authorship of the text.
3) *Current Directions:* At the moment, the CyberSecurity Lab at the University of Louisville is perusing two behavioral artimetrics projects. One project looks at the profiling of vocabulary for Internet chat bots with the goal of identifying a particular bot in new contexts [4]. The second project is aimed at performing voice-based authentication of non-biological speakers such as text-to-speech software, robots, and GPS units.

   Gesture recognition is another area currently being actively researched and is directly applicable to robot behavior authentication. Gestures form an integral part of human communication and are primary candidates for extending the communicative abilities of social robots [95]. In many cases, robot gestures are not produced at run-time, but are prerecorded for specific situations [95]. The latest research aims to produce gestures coupled with the semantic of situations in a dynamic fashion. Consequently, a number of virtual and physical robot systems have been developed, which contain a diverse spectrum of gestures and facial expressions [56], [45], [88]. Artimetrics researchers could record such body language and use it for authentication purposes. Currently no results describing artimetrics systems based on gestures have been reported, but this will soon change as projects are under research in the authors' labs to explore this exciting new area. Below, we present a nonexhaustive list of currently available artificial gesturing systems overviewed by Salem et al. [95] and Kim et al. [56]. As this is a relatively new area of research, we anticipate a lot of developments in this area in the near future and consequently great development in gesture-based artimetrics.
4) *Robot Gestures:* In the world of physical robots, Maggie [41], a personal robot, is one example of a system equipped with a set of predefined gestures, which is also capable of learning gestures from its users. Mel [100], a penguin robot, is capable of demonstrating a set of predefined gestures to indicate engagement behaviors. Fritz [11], a communication robot, uses facial expression, eye-gaze, and gestures to appear livelier while communicating with its users. Its gestures are produced during interaction, and it contains many humanlike arm movements and pointing gestures [95].
5) *Avatar Gestures:* In the domain of virtual robots (avatars), the generation of speech-accompanying gestures is a much more developed area of research [94]. For example, a conversational agent named Rea [19] acts as a real-estate salesperson. Another example is the Behavioral Expression Animation Toolkit (BEAT) [20], which produces synchronized nonverbal behaviors by predicting the timing of gestures from speech by looking at expressive phrases that coincide with the prominent syllables in the speech. Virtual Agent Max [61] represents an integrative architecture, in which the planning of content and form are combined to give meaningful nonverbal utterances [95]. Natural gestures are produced by a kinematic approach that emphasizes the reproduction of humanlike gestures combined with speech [56]. Nakano et al. [75] worked on automatic gesture production for Web-based animated avatars. Applying the above techniques to the behavior authentication of robots on the basis of the way they present themselves, perform their tasks, and communicate is another emerging area of research [4].
6) *Pros and Cons:* Behavioral methods are generally less reliable when it comes to human biometrics, but in the domain of artimetrics, behaviors of bots and human-controlled avatars are more stable compared to easily altered physical characteristics. Although behavioral artimetrics are more challenging to profile due to the large space of possible behaviors, they

present very promising current research essential to establish robot or avatar identity.

Multimodal Artimetrics

Biometric systems based solely on a single biometric may not always identify the entity (human or robot) in the most optimal or precise way. The problem is common for human and robot authentication: some robots might not possess a certain trait that is being recognized; that is, industrial robots might have similar facial features but different voices, gaits, or behavior. Thus, multibiometric system research is emerging as a trend, which helps to overcome the limitations of a single biometric solution [49]. This is especially useful in the presence of complex patterns, conflicting or misleading behavior, abnormal data samples, and intended or accidental mischief. A reliable and successful multibiometric system normally utilizes an effective fusion scheme to combine the information presented by multiple matchers.

Over the last decade, researchers tried different biometric traits with sensor, feature, decision, and match score-level fusion approaches to enhance the security of a biometric system [50], thus enhancing the security and performance of the authentication system. Multimodal biometric approaches improve the overall system accuracy and address issues of nonuniversality, spoofing, noise, and fault tolerance.

Most common approaches in multibiometrics currently rely on multimodal systems, where numerous strategies for decision making are employed. The most successful ones are based on rank-level, decision-level, and match score-level fusion [50]. Other approaches (multisensor, multialgorithm, multiinstance, and multisample) are not as popular due to the overhead associated with either multiple devices, multiple samples stored in the database, or extra time required to run different algorithms. The first article combining face and fingerprint human identification as a true multimodal system was based on match-level fusion introduced by Jain. It is included in the comprehensive review of all multimodal systems [48]. We postulate that in a similar manner, combining behavioral and physical artimetrics in robot authentication or in the virtual worlds can be utilized as part of a physoemotional artimetric system, which is a multimodal system. In addition, another concept of a multidimensional system crossing over between virtual and real worlds can be explored. This multidimensional authentication is the visual authentication of avatar through its creator authentication and vice versa. Research in this domain is emerging, with a number of projects being conducted at BTLab, University of Calgary. Although multimodal system research has become very popular over the past few years, it carries certain challenges. One is the amount of information that needs to be processed such as associated technological and management challenges of obtaining, securely storing, and accessing multiple databases. Another is the increased cost of developing and maintaining such a system and slightly increased processing time, mainly due to the addition of a fusion module. Finally, in the presence of multisource data processing and decision making, certain dimensionality reduction techniques are necessary to ensure real-time system performance.

Applications and Open Problems

There are numerous applications and implications for the methodology of robot and avatar recognition through applying biometric principles to both appearance and behavioral characteristics and utilizing multimodal and multidimensional information fusion.

One outcome is preventing malicious intelligent software from obtaining access to information or system resources and granting it to authorized agents and by doing so, improving the security of virtual communities, social networks, and the country's cyber infrastructure. With exponential growth in the abilities of artificially intelligent agents (bots, software weapons, viruses, and so on) comes the pressing need to secure information and resources from access by unauthorized agents, while at the same time allowing seamless access for the approved software. Behavior-based profiling of software agents provides an unobtrusive way of separating helpful bots from malware. Additional research in artimetrics is expected to produce novel behavior-profiling approaches specifically designed to take advantage of the unique psychology of artificially intelligent programs. Current research on telling humans and robots apart [121], [2], [6], [12], [72] demonstrates this promising direction of research, while there is still a lot of work to be done.

Finding out which agent has performed a given task, in case a number of possible alternatives exist (for demanding responsibility or assigning a reward) in collaborative environments, is another open area of research. Behavioral profiling can be used to uniquely identify a specific type of bot and potentially the bot's owner. Examples of such preliminary work can be found in click fraud and virus detection research. In both domains, unique behavioral signatures can be obtained (sometimes indirectly) from the software agent and can be matched up with known behavioral signatures leading to the attribution of the attack to a particular hacker or a mischievous group.

Securing the interaction between different components of intelligent software or between a human being and an instance of an intelligent software/robot is also an area of high importance for robot security domains. Botnets, groups of intelligent cooperating agent and mixed robot/human teams, are quickly emerging in various applications. Securing their communications is important for further progress in e-commerce, virtual community development, construction, military, and any other industry with heavy reliance on team-based efforts. To communicate securely, identities of all parties wishing to exchange information need to be determined with a high degree of accuracy. Consequently, it is important to develop automatic algorithms, which would give robots the ability to recognize other robots and human beings they are working with. This is another area with a high impact but many unanswered questions, specifically related to numerous alternatives that exist for robot communication (i.e., signals, gestures, voice, and text commands).

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Another aspect open for discussion is identity management. Although numerous algorithms exist to authenticate the identity of specific robots/computers on the basis of digital signatures and cryptographic networking protocols, robots have a better chance of fitting in human-dominated environments if they utilize a humanlike approach to identity management, which is advocated in this article. Other applications include detecting cheating in games on the basis of assistance from AI software, providing visual and behavioral search capabilities for virtual worlds, and making it possible for scientists in fields as diverse as biology, communications, and e-business to securely communicate with intelligent assistants and robots. Development of methods presented in this article not only provides a broad base for future solutions in those domains but also opens up new issues related to differences in human and robot behavioral profiling, collaborative environments, features, and unique specifics of virtual environments that need to be taken into account in real-time methodology integration and testing.

Conclusion

This article introduced a new subfield of security research, which transforms and expands the domain of biometrics beyond biological entities to include software and hardware robots, which are rapidly becoming a part of the modern society. Artimetrics research builds on and expands such diverse fields of science as forensics, robotics, stylometry, computer graphics, and security. This article presented a solid motivation for security research in the field of robotics and cyberworlds, including six scenarios for automated matching algorithms followed by the comprehensive survey of robots and methods for robot dataset creation. Description of visual, behavioral, and multimodal artimetrics constituted the core of methodology, with applications and implications of this emerging area further outlined.

The presented research into trustworthy authentication of robots will make society safer and better prepared for the accelerating integration of intelligent technologies into everyday life. Potential benefits come from the applications of the developed algorithms in many diverse areas, for example, recognition of military robots, preventing malicious intelligent software from obtaining access to resources, securing communication between different intelligent agents in virtual communities, determining authorship rights to the results of computation and creative output produced by an AI entity, and identifying semiautonomous software tools used by hackers.

Potential directions for future artimetrics research include the investigation of other visual and behavioral approaches to robot security on the basis of the appearance of new characteristics and abilities in the robots of tomorrow. Even today, it would be possible to expand robotic biometrics beyond faces and vocabulary to intelligent software agents, which mimic higher-order human intelligence. Some examples are provided below, but the list will unquestionably grow as our success with AI technologies progresses and we obtain programs, which are as creative and unique as human beings. We already have programs capable of composing inspiring music [26], drawing beautiful paintings [25], and writing poetry [14], and limits to the known abilities of machines are continuously being extended. It is already technologically feasible to look at profiling text-to-speech software on the basis of voice recognition, translation software on the basis of linguistic signatures, and authentication of game-playing bots on the basis of the strategies employed as demonstrated by the authors [117], [119].

Some other open problems are generation and evaluation of the quality of virtual entity databases and emerging research on face recognition in the virtual world. Such issues as emotion recognition, face recognition in the presence of aging, various geometrical underlying models, different approaches to virtual face representation, and displaying options provide a broad variability of avatar faces. Direct comparison with human face databases and testing the performance of recognition approaches on such databases versus human databases are an exciting unexplored domain of research. Evaluating the degree of variability of avatar databases is another open problem.

It may also be possible in the future to profile different search engines on the basis of the results they produce. Pattern recognition algorithms such as those used for optical character recognition or for biometric recognition can be profiled on the basis of the error rates. Artificial life and computer viruses can be tracked on the basis of their behavioral signatures, and game characters on the basis of a combination of visual and behavioral traits. As hardware robots continue to improve in their humanlike abilities and appearances, potential physical biometrics worthy of examination may include gait, keystroke dynamics, signature, and body part geometry.

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Terrain Reconstruction of Glacial Surfaces

By Stephen Williams, Lonnie T. Parker, and Ayanna M. Howard

Robotic Surveying Techniques

The capability to monitor natural phenomena using mobile sensing is a benefit to the Earth science community, given the potentially large impact that humans have on naturally occurring processes. Such phenomena can be readily monitored using networks of mobile sensor nodes that are tasked to regions of interest by scientists. In our article, we hone in on a very specific domain, elevation changes in glacial surfaces, to demonstrate a concept applicable to any spatially distributed phenomena (e.g., temperature or humidity). Our article leverages the sensing of a vision-based odometry system and the design of robotic surveying navigation rules to reconstruct scientific areas of interest, with the goal of monitoring elevation changes in glacial regions. The reconstruction methodology presented makes use of Gaussian process (GP) regression to combine sparse visual landmarks extracted from the glacial scenery into a dense topographic map. Further, this method allows for the natural inclusion of a priori terrain knowledge, such as existing digital elevation models. Results from this system are presented from a three-dimensional (3-D) glacial simulation

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modeled after actual field trials on Alaskan glaciers. Additionally, we introduce a theory behind spatial coverage, in the context of sampling, as achieved by an intelligently navigating agent. Finally, we validate the output from our methodology and provide results and show that the reconstructed terrain error complies with acceptable mapping standards found in the scientific community.

Nowadays, the ability to understand the causes and effects of climate change is one of the foremost task under consideration in the scientific community. Since the 1970s, scientists have gathered weather-related measurements from around the globe to study this phenomenon, model the major contributing factors, and predict the global ramifications. It has been discovered that the world's glacial regions are particularly sensitive to changes in climate, the dwindling ice caps are but one sign of this region's increasing temperatures [1], [2]. Because of the sensitivity of these regions, scientists have focused data gathering efforts toward the poles, setting up networks of automatic weather stations in Greenland and Antarctica [3]. These stations are expensive to install and maintain, yet provide only sparse spatial resolution in these critical areas. To augment the data collection mechanisms available to climate scientists in harsh, glacial terrain, a multiagent robotic sensor network has been proposed [4]. The network would consist of multiple autonomous robotic rovers equipped with a customizable sensor payload. The scientists would define the region of interest and desired spatial resolution and then task the network to execute the data-gathering mission.

(a)

(b)

Figure 1. Examples of dynamic terrain hazards encountered during field trials in glacial environments: (a) a large crevasse and (b) exposed ice with irregular surface and melt-water pools.

The multiagent nature of the proposed system poses certain design constraints. Most notably, because the system will consist of many robotic nodes, each node must be inexpensive. This pushes the design away from centimeter accuracy global positioning system (GPS) units and military-grade inertial measurement units (IMUs) toward consumer-grade sensing equipment. However, consumergrade sensing generally does not have the localization accuracy necessary for the positioning of the robotic nodes into the requested sampling topology. Commodity sensors must, therefore, be augmented with other real-time measurements to create a higher-accuracy localization system.

For efficient traversal to the designated location, each robotic node must plan a safe and efficient path through the terrain. Although the algorithms employed by global path planners differ significantly, from the dynamic programming methods of Dijkstra's algorithm to the random sampling methods of rapidly exploring random trees [5], all planning strategies require a map on which to plan. Coarse-scale maps are generally available from remote sensing technologies. However, at typical resolutions greater than 100 m [6], these maps are unable to capture rover-scale terrain structures that could impede travel or affect the accuracy of derived scientific measurements. Additionally, glacial terrain is often dynamic in nature, with snow dunes and exposed ice changing shape and location over time. Examples of these time-varying terrain elements are shown in Figure 1. In order for the planned paths to be useful, the coarse-scale terrain map must be augmented with local-scale features encountered by the robotic platform during the traverse. Ideally, the terrain should be sensed or predicted before the platform encounters these obstacles, allowing new paths to be planned far in advance.

In addition to improving navigational performance, the terrain reconstruction itself can be a key scientific data product. Currently, many remote sensing methods lack the instrumentation necessary to collect important spatial details of portions of the glaciers of interest to Earth scientists [3]. Sparse automatic weather stations cannot provide the preferred spatial detail. Furthermore, human field expeditions, especially for Arctic surveys in regions where glacial melt creates significant hazards, cause safety concerns. Even if the centimeter resolution desired by Earth scientists is obtainable by modern sensing techniques, such as inferometric synthetic aperture radar (InSAR), the specific areas of interest may not always be accessible. For example, naturally occurring occlusions can prevent direct line-of-sight measurements by remote sensing instrumentation, while temporally based constraints, such as weather conditions or satellite orbits, may preclude measurements at the desired time.

For example, the SeaMonster project [7] relies on shortterm experiments (10–15 days) to measure the transient hydrological processes taking place in Lemon Creek glacier near Juneau, Alaska. Their article on seasonal snow melt modeling requires registering data collected from static sensor nodes with elevation maps. Although time-variant measurements obtained from the static nodes are collected on a semidaily basis, they must rely on the same, outdated digital elevation map (DEM) data at each measurement time step, i.e., every one to two days. A robotic survey system could provide spatially relevant terrain data in synchronization with this sampling frequency, allowing subtle changes in topography to be correlated with other measurement data. Although high-resolution imaging techniques such as InSAR are very powerful, conducting repeatable surveys with a robotic surveyor system may prove to be a more flexible alternative [8]. The value in developing robotic surveying solutions is found not only in terrain reconstruction but also for other applications requiring the intelligent sampling of geophysical science information. This is particularly true when such information is spatially distributed and not easily accessible by remote sensing technology [4], [9]. Other motivations include mineral prospecting or chemical concentration monitoring in soil [10], [11].

In the following sections, a vision-based simultaneous localization and mapping (SLAM) algorithm is described that was tailored to meet the challenges of using vision systems in low-contrast, glacial environments. As a byproduct of calculating the robot's pose estimate, the SLAM system also estimates the positions of a large number of terrain landmark points. An adaptive terrain reconstruction methodology is proposed that creates a topographic terrain map using these vision-based terrain measurements as input. Additionally, prior terrain knowledge, such as course-scale satellite elevation measurements, can be incorporated into the terrain model in a natural way, further improving the reconstruction quality. This is originally motivated by the need for forward-looking maps for path planning algorithms. However, once the focus changes to maps as the end product, different planning mechanisms are needed. Surveying strategies are discussed in the context of sampling methodologies, as well as methods for selecting the surveying path parameters based on prior knowledge of the terrain and common mapping standards. We also introduce the concept of science-centric coverage (SCC), a spatially relevant performance metric, to better evaluate the meaning of collected science information as it relates to the surveying strategies. Both the vision-based terrain sampling methods and the described surveying path planners are validated within a simulation environment created to mimic a glacier field test site.

Robotic Sensor Network

Previous arctic robotics projects, such as Nomad out of Carnegie Mellon University [12] and Mobile Arctic Robotic Vehicle for Ice Navigation from the University of Kansas [13], showcase the ability of the mechanics of a robot to survive the inhospitable climate of glacial environments. However, each of these projects involves the construction of a single, expensive robotic agent. Such an approach is not practical for the development of multiagent systems, where potentially dozens of robotic agents will be used. Three low-cost prototype mobile sensor nodes were constructed as part of this research, enabling data collection and autonomous field testing in analogous arctic terrain.

High terrain mobility is required for testing and proper execution of science missions. Although much of the rover's time will be spent in the central regions of the glacier, the project goal is to construct a system capable of traversing the widest range of expected terrain possible. Typically, the areas of most interest to scientists occur at the extremes of the environment. Collecting data about a forming glacial lake requires descending into the surrounding basin, as shown in Figure 2, whereas investigating the glacier-mountain boundary requires ascending steep slopes.

For these reasons, a snowmobile chassis was selected as the base for the SnoMote prototype robotic mobile sensor [14]. The chassis, based on a one-eighth scale remote control model, was heavily modified to incorporate a dualtrack design. The modified platform has been equipped with an onboard embedded computer, consumer-grade GPS unit for global localization, and a wide-angle monocular camera for real-time image processing. Only a minimal amount of sensing was incorporated into the rover design to test the extents to which the vision system could supply the situational awareness and terrain assessment needs of the mobile rover.

Vision-Augmented Localization

Because many agents will be required to perform a data collection task, each agent must cope with low-cost, commodity sensors. However, consumer-grade GPS receivers and IMUs do not have the localization accuracy necessary to position the robotic nodes into the request sampling topology. These sensors must be augmented with additional information to produce a viable system. In particular, vision is an attractive option. It is the sensing modality relied upon most by humans, and it has been shown to be effective for both the

Figure 2. The SnoMote prototype rover descending into a glacial lake basin at the test site in Juneau, Alaska.

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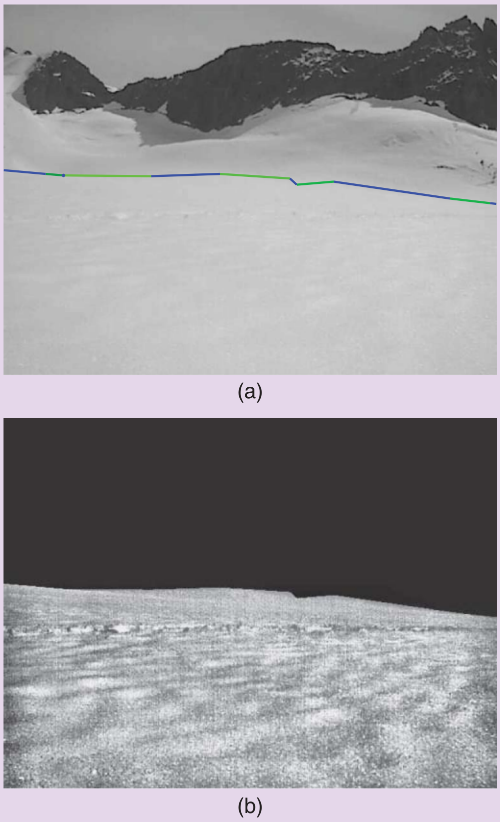

Figure 3. (a) Background image features, such as the distant mountains, can interfere with future image processing steps. By detecting the horizon line in the image, these regions can be identified and removed. (b) The results of the CLAHE contrast enhancement of the masked image. For the first time, the underlying structure of the scene is clearly visible.

Mars rovers [15] and Defense Advanced Research Projects Agency (DARPA) Grand Challenge vehicles [16].

To augment the GPS localization system, a visual odometry system has been implemented based on SLAM techniques. Vision-based SLAM systems seek to estimate the 3-D pose of the camera by tracking the coordinates of visually distinct features in the environment. As the features move in image space, the relative motion is used to update the position of the camera as well as estimate the 3-D location of the features themselves. This requires that image features be reliably extracted and matched within the image stream. However, glacial environments generally lack these types of distinctive features. The following sections briefly describe the vision system and sensor fusion techniques employed in the vision-augmented localization subsystem.

Image Preprocessing

Since standard feature detectors search for pixels exhibiting strong directional gradients, the foreground image gradient must be boosted for these detectors to properly perform in low-contrast glacial environments. Ideally, the image enhancement should be nonuniform, adaptively enhancing the foreground regions while leaving areas of sufficient contrast alone. A contrast-limited adaptive histogram equalization (CLAHE) preprocessing stage has been shown to drastically improve both the detection rate and matching consistency of standard feature detectors when applied to glacial scenes [17].

CLAHE separates the image into different contextual regions. Within each region, a histogram equalization procedure is calculated and stored. To prevent blocking artifacts, the level of equalization performed is interpolated from neighboring regions. Finally, to prevent overenhancement of local areas, a contrast limit is imposed.

As the goal of the contrast enhancement procedure is to extract features from the snowy foreground, the algorithm performs best if background elements, such as sky and distant mountains, are first removed. However, standard image segmentation algorithms, such as region-growing methods or machine learning-based approaches, generally use information local to the examined pixel to make segmentation decisions. The properties of glacial images make local examination problematic. Overcast skies, common in glacial environments, often share the same color range as the ground plane snow. To that end, a horizon line detection scheme has been developed, which uses multiple visual cues to rank candidate horizon segments and then constructs a horizon line consistent with those cues [18].

Strong line segments are first extracted from the image. A minimum segment length constraint is enforced to remove the large number of noise-induced edges. A set of heuristic properties, such as segment length and color consistency, are then calculated for each remaining candidate segment. A combined weight is calculated for each candidate segment as a product of the individual weights. The top scoring candidate is selected as a seed segment for the horizon line. A greedy search is then conducted to find additional horizon line segments to connect to the seed segment. Candidate line segments that exhibit weak visual cues serve to reinforce the path of stronger segments while segments with strong visual cues have the ability to redirect the path of the horizon. Figure 3 shows the results of the preprocessing steps on a typical glacial image acquired during field trials on Mendenhall Glacier, near Juneau, Alaska.

Feature Extraction

With the image suitably enhanced, one of a number of common keypoint detectors, such as Harris or Scale Invariant Feature Transform (SIFT), can be used to meet the feature detection needs of the visual odometry system [19]. After features have been extracted from the new frame, the detected features must be matched with the existing landmarks. As the size of the landmark database grows, the calculation time for the feature association also grows. In this application, where the expected rover path is piecewise straight, the landmarks that are behind the rover are unlikely to ever be viewed again. Using this insight, the database is periodically culled of landmarks that are significantly behind the camera's image plane. In practice, this limits the number of landmarks that must be actively maintained while allowing the total number of landmarks used during the traverse to increase without bounds. This also means that landmarks are only active for a short time period, reducing problem-matching landmarks that were observed under different lighting conditions or at large angle differences. Although the small active database size also means that loop closures are unlikely to occur, the inclusion of even low-quality GPS information in the navigation solution prevents the system from drifting over large time periods. Figure 4 shows an example of the resulting features calculated using the SIFT detector on an image from the same Mendenhall Glacier field trial. The detected features tend to track the small-scale surface undulations, visible in the enhanced image as alternating light and dark bands.

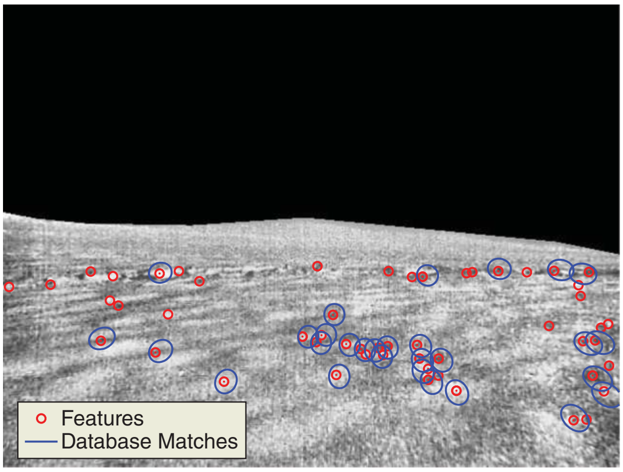

Figure 4. SIFT features extracted from preprocessed images obtained from the Mendenhall Glacier field trial. The landmark covariances have been projected into the image plane for matched features.

GPS Fusion

Position drift is one of the fundamental issues when using any incremental localization system, including SLAM. As the system runs, small errors accumulate, resulting in significant localization error over time. To remove this drift, global position information, in the form of low-accuracy GPS data, has been fused with vision-based SLAM.

Within this SLAM implementation, the robot state distribution is estimated using a particle filter, which approximates the true robot state distribution from a set of weighted samples. To incorporate the GPS measurements into the state estimate, an additional weighting step is applied to each particle based on the position fix and positional errors reported by the GPS. Particles that naturally evolved near the GPS measurement are resampled and allowed to propagate forward while particles with states far from the GPS measurement are discarded. Since the particle trajectory is unchanged by the weighting process, corrections to the landmark positions are not needed. Results of the full localization system within the simulated environment show localization errors remain under 1.0 m during a majority of the traverse using GPS measurements with a nominal accuracy of 10 m.

Vision-Based Terrain Reconstruction

In order for each robotic agent to achieve its goal location within the sensor network, a path plan must be generated that keeps the rover on safe, traversable terrain. However, before such a plan can be generated, an appropriate map is required, which captures the types of terrain obstacles present in a given environment. Specifically, the major obstacles in glacial environments are slope based [20], [21], making knowledge of the rover's orientation in the environment important when determining traversability. Hence, a topographic map is a natural choice, allowing the planning algorithm to predict the rover orientation over the entire path.

The SLAM algorithm produces a set of 3-D landmarks on the terrain surface as a by-product of estimating the rover's pose. Although this is considered a map within the context of SLAM, it is difficult to extract the terrain slope from these noisy surface elements or reason about the terrain between sparse landmarks. Additionally, SLAM landmarks are localized incrementally by viewing the landmark with increasing amounts of parallax. This means that the most accurate landmark positions will be obtained as the rover passes by the landmark position, and landmarks that are directly in front of the rover will retain large amounts of uncertainty. This has detrimental implications for use in path planning, where the terrain structure in front of the rover is of far more interest than the terrain behind.

In contrast, a common terrain reconstruction procedure within the geostatistics field involves GPs. A GP intrinsically handles measurement uncertainty, allowing the calculation of both the maximally likely terrain surface and the terrain uncertainty. Additionally, the GP uses information about observed terrain to predict unobserved terrain, albeit with increasing levels of uncertainty. This alleviates the issues with using SLAM landmarks directly. To supply data to the GP interpolator, geostatistical models often use GPS survey data collected in a uniform grid or other sampling topology designed to capture the observed terrain variation. The positional errors associated with GPS survey data tend to be small and relatively uncorrelated, making this a good fit for GP interpolation. While the use of GPS measurements and high-accuracy laser scan data is common in the GP literature, vision-only reconstructions are rare.

A terrain reconstruction method is presented that uses the sparse landmark position estimates from the localization system as input to a GP interpolation system. Additionally, the GP can incorporate a priori knowledge of the terrain structure through the use of a mean function. The predicted terrain is then pulled away from the mean in response to measurements of the real terrain. This allows the course satellite data to bootstrap the reconstruction system while providing a mechanism for correcting and augmenting this information with measurements on the ground.

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Gaussian Processes

A GP is a collection of an infinite number of random variables with a jointly Gaussian distribution [22]. This may be interpreted as a distribution over continuous functions, similar to how a Gaussian variable defines a distribution over real values. Instead of sampling a value in $\mathbb{R}^N$ from the Gaussian variable, a continuous function, $f(\vec{x})$, is drawn from the GP that maps an input vector, $\vec{x} \in \mathbb{R}^N$, to an output value, $y \in \mathbb{R}$. A GP is defined by a mean function, $\mu(\vec{x})$, that describes the mean output value of all possible sample functions evaluated at the input, $\vec{x}$, and a covariance function, $k(f(\vec{x}_i), f(\vec{x}_j))$, that describes the correlation between any pair of output values. The choice of the mean and covariance functions allows prior knowledge of the function's behavior to be encoded in the GP framework.

Commodity sensors must be augmented with other real-time measurements to create a higher accuracy localization system.

To perform interpolation, the GP is conditioned on a set of known measurements [22]. The resulting GP posterior describes only the subset of sample functions that pass through the measurement points. A set of unknown output values, $Y^* = \{y_j^* | \, j = 1,\dots,Q\}$, can then be queried, corresponding to a set of known input values, $X^* = \{\vec{x}_j^*\}$. The output values are conditioned on a set of known measurements, $Y = \{y_i | \, i = 1,\dots,P\}$, corresponding to a second set of known input values, $X = \{\vec{x}_i\}$. The GP posterior mean and covariance satisfying these conditions are shown in (2) and (3) (with a full derivation available in [23]).

$$p(Y^* | X, Y, X^*) \sim \mathcal{N}(\mu^*, \Sigma^*), \quad (1)$$

$$\mu^* = \mu_X + \Sigma_{Y,Y^*} \cdot \Sigma_{Y^*,Y^*}^{-1} \cdot (Y - \mu_X), \quad (2)$$

$$\Sigma^* = \Sigma_{Y,Y} - \Sigma_{Y,Y^*} \cdot \Sigma_{Y^*,Y^*}^{-1} \cdot \Sigma_{Y,Y^*}^{T}, \quad (3)$$

where μ_S is a vector of values produced by evaluating the mean function, $\mu(\cdot)$, over the set, S, and Σ_{S_1,S_2} is a covariance matrix constructed by evaluating the covariance function, $k(\cdot,\cdot)$, with each pairwise combination of values from sets S_1 and S_2.

A GP can also incorporate measurement uncertainty into the reconstruction, if that uncertainty may be modeled by additive independent Gaussian noise. In that case, the measurement covariance matrix, $\Sigma_{Y,Y,}$ is simply augmented by diagonal matrix containing the uncertainty of each measurement.

Finally, while many covariance functions are possible, a common choice is the squared exponential function listed in (4). This covariance function is derived from a Gaussian kernel, exhibits rotation and translation invariance to the inputs, and is infinitely differentiable or infinitely smooth. At this time, the simulation environment consists only of a smooth terrain near the center of a glacial flow, modeled after the terrain encountered during field trails. One field test was conducted in the upper section of the glacier terminus, where the underlying ice is exposed. However, even this terrain is locally smooth. This makes the selection of the standard Gaussian kernel covariance function a natural choice.

$$k(f(\vec{x}_i), f(\vec{x}_j)) = \alpha \exp\left(-\frac{1}{2}(\vec{x}_i - \vec{x}_j)^T \Gamma (\vec{x}_i - \vec{x}_j)\right), \quad (4)$$

where Γ is a diagonal matrix of elements $1/\gamma_1, \dots, 1/\gamma_N$, and α is a scaling factor. The variables in the $N+1$ dimensional set $\alpha, \gamma_1, \dots, \gamma_N$ are known as the hyperparameters for the squared exponential GP.

To train the hyperparameters, the locations, X, and elevations, Y, of a small segment of the terrain were provided to the GP. The values of the hyperparameters α and γ were varied over a large range, and the corresponding terrain reconstruction error was calculated from ground truth elevation data. Since the orientation of the world coordinate system should not affect the GP results, the length scales in the two dependent variables are set equal, $\gamma_x = \gamma_y = \gamma$. The values associated with the lowest reconstruction error, $\alpha = 10.0$ and $\gamma = 315.0$, were selected for use in the GP regression in all following results.

Other research into GPs has shown that nonstationary covariance functions allow the reconstruction to better model abrupt elevation changes [24], [25]. Efforts at the University of Sydney have shown improved terrain modeling performance with GPs that use neural network-inspired covariance functions [26]. If future missions require the reconstruction of more extreme terrain with severe discontinuities, more advanced nonstationary covariance functions can be employed.

Visual Landmarks

The visual SLAM algorithm within the localization system produces a set of 3-D point estimates that lie on the terrain surface as a by-product of the localization process. Although these point estimates are superficially analogous to GPS data or laser scan measurements, these data were collected opportunistically while the robot performs a traverse, rather than with the explicit goal of capturing terrain variations. These visual landmarks also cover the terrain only sparsely, with landmarks near the rover's path occurring far more frequently than landmarks at significant distances. While this may be suboptimal from a terrain sampling standpoint, no additional travel is incurred by the rover to collect these data.

Further, the uncertainty of each SLAM landmark is a joint Gaussian distribution in both the dependent variables, (x, y), and the independent variable, z. Inclusion of uncertainty in the dependent variables has been studied in the domain of GP regression. One approach conditions the GP on the distribution from which $\vec{x}$ is drawn, rather than on $\vec{x}$ itself. The result of

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this formulation takes the form of a correction to the standard GP regression results, as shown in (5)–(7) [27]. For this method to be applied, each landmark covariance is converted into a joint distribution on x and y, and an independent additive noise term on z by alternately marginalizing out the other set of variables from the joint distribution. Because of the highly directional nature of visual SLAM landmark estimates, removing the dependency of x and y, even from covariances with a small volume, results in a large elevation uncertainty. For this reason, only those landmark estimates whose depth uncertainty has collapsed to a small region are considered for inclusion in the GP terrain reconstruction.

$$
\begin{aligned}
p(f(\vec{x}^*)|\mu_{x^*},\Sigma_{x^*}) &= \int p(f(\vec{x}^*)|\vec{x}^*)p(\vec{x}^*)dx^* \\
&\approx \mathcal{N}(m(\vec{x}^*), v(\vec{x}^*)), \qquad (5)\\
m(\vec{x}^*) &= \mu^*, \qquad (6)\\
v(\vec{x}^*) &= \Sigma^* + \frac{1}{2}Tr\left\{ \left.\frac{\partial^2\Sigma^*}{\partial\vec{x}^*\partial\vec{x}^{*T}}\right|_{\vec{x}^*=\mu^*} \Sigma_{x^*}\right\} \\
&\quad + \left.\frac{\partial\mu^*}{\partial\vec{x}^*}\right|^{T}_{\vec{x}^*=\mu^*} \Sigma_{x^*} \left.\frac{\partial\mu^*}{\partial\vec{x}^*}\right|_{\vec{x}^*=\mu^*}, \qquad (7)
\end{aligned}
$$

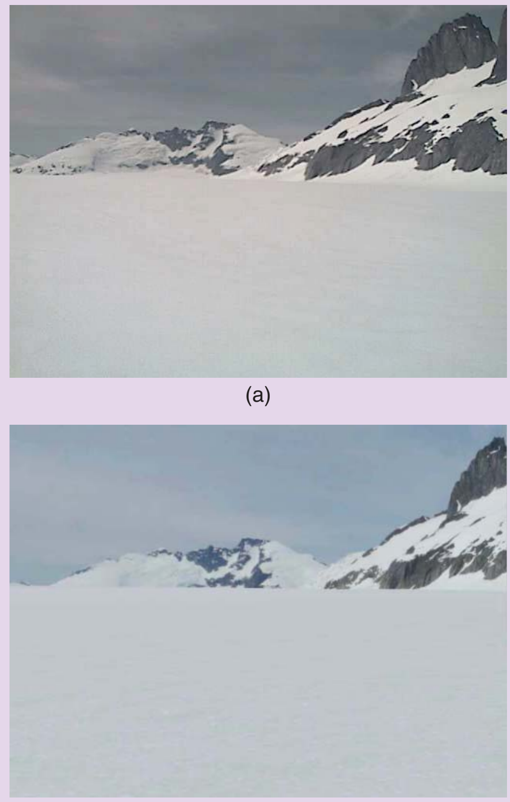
where $p(\vec{x}^*) \sim \mathcal{N}(\mu_{x^*}, \Sigma_{x^*})$.

Satellite Elevation Data

DEMs produced by satellite missions, such as the Shuttle Radar Topography Mission (SRTM) or ICESat, average the terrain elevation over a large area compared with the size of the rover. Although this information cannot capture the local-scale hazards faced by the robotic sensor node, it can serve as an indication of large-scale terrain variations. Within the GP framework, a mean function, $\mu(\vec{x})$, is specified. This is typically set to a constant value, calculated from the mean of all the observation values. The GP then models the terrain deviation from the mean. However, if a better terrain elevation expectation is available, this can be easily incorporated into the GP. In particular, while it is referred to as a mean function, it need not be written in analytical form. It simply must provide terrain elevations at the measurement locations, X, and the query locations, X^*. This can be easily accommodated using simpler interpolation methods on the satellite data or even from online mapping services such as U.S. Geological Survey (http://www.usgs.gov) or Google Earth.

Simulation Examples

The prototype robotic network has been fielded at several test sites on Mendenhall Glacier near Juneau, Alaska. However, performing numerical evaluation of the vision system is difficult from the field trial data. An accurate terrain map of the test site locations is unavailable, making assessment of the terrain reconstruction problematic. To perform comprehensive numerical analysis of the vision system results, a 3-D robotic simulation was developed. This simulation system, which uses Gazebo [29] as its base, has been extended to provide a visually faithful environment, including realistic large-scale terrain, localscale hazards, and background imagery. Figure 5 shows a visual comparison of the simulated terrain and the real terrain from which it was developed [30]. As the simulation can provide true robot pose information and operates with a known terrain topology, it is an ideal testing platform for localization and terrain reconstruction algorithms.



(a)

(b)

Figure 5. A visual comparison of (a) the Mendenhall Glacier field trial site, the real terrain at a field test site, and (b) the Gazebo simulation, the resulting simulated terrain.

To test the terrain reconstruction system, one of the Mendenhall Glacier field trial sites was reconstructed within the simulation environment. The control commands from one of the field trial traverses were sent to the simulated rover while the augmented localization algorithm executed against the simulated camera images. During the traverse, any SLAM landmark whose final $1-\sigma$ covariance ellipse was no larger than 0.5 m was logged to an external database. During the simulation trial, approximately 50,000 surface landmarks were sufficiently localized, a vast majority of which occurred very near the rover's path. Because of the proximity of these landmarks, the information they provide is largely redundant. To reduce the number of measurements that must be processed by the GP, only those landmarks that were initialized more than 5 m from the rover's position are used within the reconstruction. This reduces

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the set to approximately 5,000 landmarks disbursed over the 600 m $\times$ 600 m simulation site.

To compare the performance of the terrain reconstruction system, three different methods have been tested. The first uses a simple linear triangular mesh interpolation method. The Delaunay triangulation [31] is formed from SLAM landmark positions. Any query point that falls within the triangulation is estimated using the plane formed by the triangle's vertices. Because query points must fall within a Delaunay triangle to be estimated, this method only produces terrain estimates within the convex hull of the input measurements. Also, there is no obvious mechanism for incorporating measurement uncertainty or a priori information into a triangular mesh model.

The second reconstruction incorporates the sparse visual SLAM landmark data into a GP model. Unlike the triangular mesh interpolation scheme, the GP model is valid over all of $\mathbb{R}^2$. The mean function used within this reconstruction is a constant derived from the mean elevation of all landmarks used within the reconstruction. The final reconstruction is based on a GP model using the sparse SLAM landmarks as measurements, incorporating a nonconstant mean function. Raw elevations were extracted from the best available SRTM data products for the simulated test site. These elevation values were used to generate a triangular mesh terrain model capable of interpolating the elevation at any point within the test environment. While the simulated environment is derived from more than 200,000 unique elevations, the raw DEM contained only 64 values. The resulting terrain reconstructions of the simulation environment after the completion of the preplanned path are shown in Figure 6.

Perhaps, the most striking aspect of the three reconstructions is the limited data provided by the triangular mesh. Only 26% of the terrain could be reconstructed after the traverse was completed. In contrast, both GP reconstructions were able to predict the elevation of the entire terrain based on the local observations, even terrain sections that were located behind the rover over the entire traverse. The landmark-only GP reconstruction is able to capture the basic structure of the terrain from the limited data provided, although significant reconstruction errors exist at the terrain boundaries. The landmark plus satellite data GP reconstruction is able to make use of the provided large-scale terrain structure, drastically reducing reconstruction errors at large distances while still adapting locally to the measured environment.

Robotic Surveying

In the previous section, a method for generating a terrain reconstruction was presented, motivated by the need to provide an accurate map for path planning algorithms when traveling in unknown or dynamic environments. However, the terrain reconstruction itself may be viewed as a valuable scientific information. To ensure the reconstruction results in a usable data product, the terrain model should comply with accepted topographic mapping standards. The GP reconstruction method discussed previously showed results based on terrain points gathered opportunistically. To ensure compliance with mapping requirements, we require survey paths designed to meet maximum reconstruction error requirements. In traditional robot surveying projects, navigation patterns typically follow a lawn mower structure [32], [33]. However, in the scientific realm, sample locations are planned to capture the distribution of environmental phenomena characteristics [34]. As such, we need to employ navigation patterns based on sampling methodologies that properly cover the space of changes in environmental characteristics. In addition, our methods must be validated based on actual mapping requirements set forth by the photogrammetric and cartographic professions.

Robot Navigation

In robotics, the coverage problem is typically defined to maximize the total area covered by a robotic system [35]. Many successful surveying techniques [32], [36] focus on performing a raster scan (i.e., lawn mower) by designating evenly distributed, linear traverses across an area of interest. By designating swath widths, this type of navigation pattern enables the system to retrieve an even distribution of samples within the shortest distance possible. Unfortunately, this static approach is usually implemented for the purpose of search and thus does not adapt to environmental phenomena measured in situ during the traverse. However, in the scientific community, coverage is defined to properly measure the space of environmental phenomena [34]. As such, our objectives are to define a navigation pattern that sufficiently samples the space of environmental phenomena and quantify performance with useful metrics as it relates to collecting scientific information. To achieve the first objective, we augment the lawn mower navigation pattern using a method called piecewise continuous [37]. The sampling path deviates around a linear reference swath based on sensed phenomena within the terrain according to a locally applied heuristic. This method empirically tests how sensed information can be used to influence navigation decisions within smooth and continuous terrains. The differentiability condition of the terrain [38] enables the use of gradient-based control rules to guide navigation. For example, the sensed terrain slope between sequential sample locations is leveraged to create a navigation policy that potentially yields a more spatially diverse set of observations.

We restrict the application of this policy to environments best approximated as C^K continuous, where $K \geq 1$. This requires that at least the first derivative of the environment surface must exist and be continuous. Based on preliminary experiments with simulated terrains, sample sets that exhibit lateral, spatial diversity are more likely to reduce reconstruction error than clustered sample sets for these types of undulating terrains. The specific heuristic applied in this article is a policy defined by a switching mechanism, alternating between gradient-ascent and gradient-descent rules for changing direction based on locally sensed features within the terrain, as described by (8).

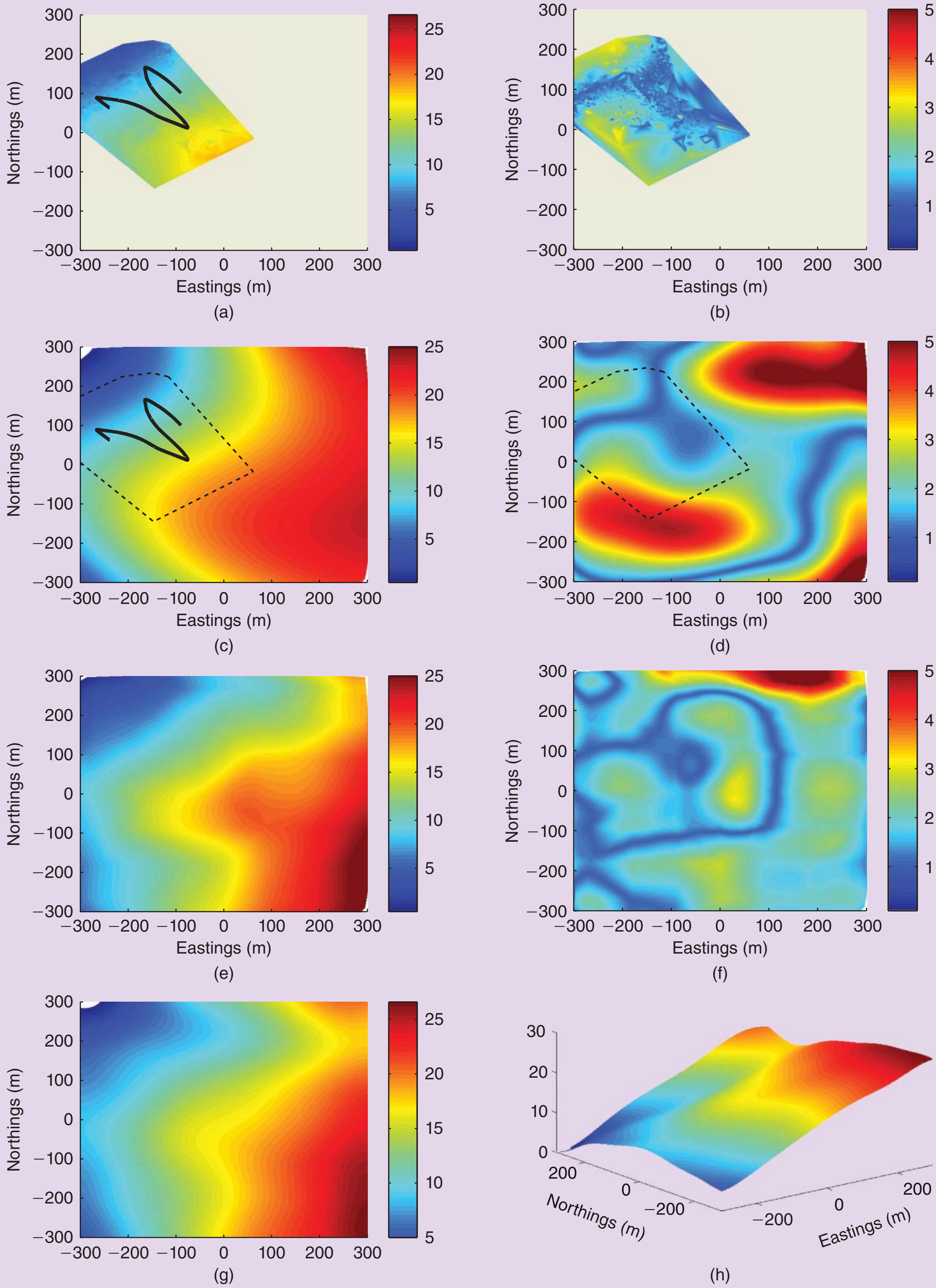

Figure 6. Terrain reconstructions using data from an example traverse. The rover's path is shown as a solid black line, and the convex hull of landmark points is indicated by a dashed line. (a) Triangular mesh reconstruction, (b) triangular mesh error, (c) SLAM reconstruction, (d) SLAM error, (e) SLAM + satellite reconstruction, (f) SLAM + satellite error, (g) ground truth, and (h) axonometric view.

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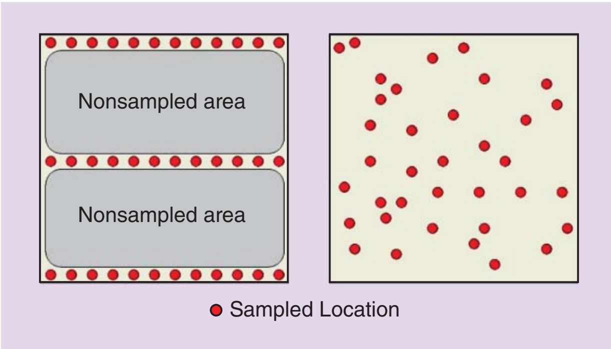

Figure 7. Traditional sampling patterns viewed in the context of navigation waypoints. While gridded sampling offers the advantage of (a) resource-efficient navigation, significant information is lost. Alternatively, (b) random sampling achieves large-scale coverage, yet incurs large resource costs as a function of required distance traversed.

$$f_{s+1}(q) = \begin{cases} \min(\vec{\nabla} f_s(q)) & \text{if } \eta = 0. \\ \max(\vec{\nabla} f_s(q)) & \text{if } \eta = 1. \end{cases} \quad (8)$$

In (8), the function $f_{s+1}(q)$ represents the next state or location of the navigating agent, $f_s(q)$ represents the agent's current state, s is the sample index, and q is the specific location of the agent. The switching feature is represented by η, a random binary value resampled whenever the agent reaches a local extrema in the terrain or when the agent reaches a lateral boundary distance from the reference swath. For example, if the agent is navigating according to reference swaths that extend east to west, then local north–south boundaries are set as a function of swath width. As the terrain characteristics at a given state are unknown, η is used to guide the agent toward different features within the terrain, increasing the lateral spatial diversity of collected samples. If no significant gradient is experienced during navigation, the policy simplifies to traditional lawn mower navigation. In contrast, employing a random sampling scheme will not only achieve the desired spatial diversity [39] but will also incur large costs in terms of distance traversed. The piecewise continuous navigation strategy generates a policy that correlates to sampling strategies found in the sampling and surveying literature [39], [40] while also considering the practicality and cost of navigating from one sample location to another. Figure 7 illustrates the traditional sampling patterns viewed in the context of navigation waypoints, while Figure 8 provides example trajectories for the two sampling strategies.

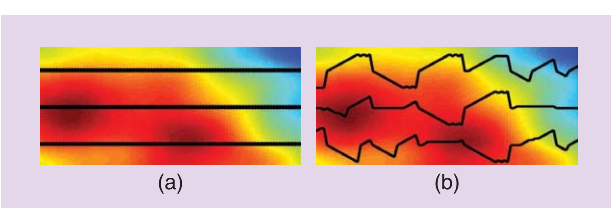

Figure 8. Example of executed rover paths illustrating the spatial coverage differences of robotic surveying navigation options. (a) Traditional lawn mower and (b) piecewise continuous.

Science-Centric Coverage

Typical navigation work in the robotics community defines coverage as the ratio of the total Euclidean distance traveled by a robotic agent, D_S, to some maximum distance, D_T. Measuring coverage in this way places attention on the agent and its performance rather than the search space and the quality of samples collected during navigation. If, instead, the search space is discretized into a finite set of possible sample locations, a more useful definition of coverage for science sampling can be generated.

We define a coverage metric relative to the cumulative sum of distances from all possible sample locations to the center of the area of interest. Percent SCC is the ratio of T_M, the sum of relative distances between actual samples, (x_m, y_m), and a reference location within the search space, (X_{ref}, Y_{ref}), to T_S, the sum of relative distances between all possible samples, (x_s, y_s), and that same reference location. This is detailed in (9).

$$\%SCC = \frac{T_M}{T_S} = \frac{\sum_{m=1}^{M} \| (x_m, y_m) - (X_{\text{ref}}, Y_{\text{ref}}) \|}{\sum_{s=1}^{S} \| (x_s, y_s) - (X_{\text{ref}}, Y_{\text{ref}}) \|}. \quad (9)$$

For each level of desired coverage designated by a scientist, we assess a measure of percent SCC, attaching with it the success of the sample set. Specifically, the performance of the samples collected is measured in the form of root-mean-squared (RMS) error.

By using the representation that SCC provides, we define distances relative to a specific point, $(X_{\text{ref}}, Y_{\text{ref}})$. This relationship prioritizes the importance of the samples collected and provides each sample with a relative weight. For our experiments, we presume an approximately rectangular, discretized search space in $\mathbb{R}^2$.

Mapping Accuracy Standards

Finally, we must ensure that the map regeneration we produce meets a predefined error maximum set forth by those interested in the science product. Although desired map accuracies can vary, we refer to the accepted accuracy standards employed by professionals in the cartographic and photogrammetry fields [41]. In the case of map elevation, the American Society for Photogrammetry and Remote Sensing (ASPRS) standard quantifies vertical RMS error specifications that dictate how a mapping product may be classified.

ASPRS standardizes the accuracy of map data when represented as a two-dimensional (2-D) contour plot, with each contour line representing a specific elevation. When seeking a map product in the form of a 2-D contour map with contour separation equal to P, the average map error estimated must not be greater than $P/6$ or one sixth the contour separation. Thus, a desired contour separation of 3 ft (0.91 m) requires an average error not greater than 0.5 ft (0.15 m). According to ASPRS, there exist three distinct classes of map accuracies based on contour line separations, ranging from 1 ft to 9 ft. The specific maximum allowable error varies depending on the needs of the scientist, but once a value is agreed upon, it provides a benchmark for validating our results. Figure 9 shows the evaluation of these navigation patterns against typical terrains, such as the one shown in Figure 6(g), relative to accepted mapping standards.

Results

We evaluate the performance of our vision system and surveying methods based on the successful reconstruction of our environment. As a test, the system has been tasked to create a Class 3 elevation map. In this context, a reconstruction is considered successful if the final elevation model meets the minimum criteria for the map type selected. This implies a maximum terrain reconstruction error of 0.46 m. The area to be surveyed is a simulation of a 600 m × 600 m field test site on Mendenhall Glacier. Using satellite elevation data, the maximum terrain variation over this area is found to be approximately 25 m. However, this is merely an estimate of the terrain variation, as each satellite measurement is actually an average elevation over a large area. Using this maximum terrain variation estimate, a set of random terrains was simulated numerically, using the procedure outlined in the "Robotic Surveying" section. Figure 10 shows the average reconstruction error of the random environments when surveyed by different path planning approaches. The maximum error requirement for the Class 3 map is superimposed on the results. From this graph, the minimum number of surveying swaths for each algorithm may be extracted (four swaths for traditional lawn mower and two swaths for piecewise continuous).

The simulation system described in the "Vision-Based Terrain Reconstruction" section has again been employed to validate the surveying path predictions. The simulated rover is placed at a starting point within the simulation, which is assumed to be a known location. The rover is then tasked to drive through a series waypoints calculated from the selected surveying pattern. During these traverses, the vision-augmented localization system maps the location of any visually distinct texture points encountered. These 3-D surface estimates are used as inputs to the GP terrain model. These surface points are analogous to GPS survey information, with the exception that the sampled locations are controlled by the visual surface appearance rather than a planned sampling scheme. In the case of the piecewise linear survey algorithm, the path actually adapts in response to the surface conditions. These decisions are based on the pose estimate of the rover, as intermediate terrain reconstructions are not available to the rover during the surveying process. Figure 11 shows the executed rover paths for each surveying strategy and an indication of the spatial distribution of the visual landmarks.

Finally, a terrain reconstruction is performed for each surveying algorithm using the GP framework described in the "Vision-Based Terrain Reconstruction" section (Figure 12). On the basis of our simulated prediction of the number of swaths required to achieve the maximum ASPRS mapping standard error for a Class 3 map (0.4572 m), our system achieves RMS error of 0.2827 m and 0.3323 m, respectively, when navigating according to the traditional lawn mower pattern and piecewise continuous navigation.

The outcome of our testing highlights two salient aspects of our article. The first point is the performance of our vision system as a sensor to generate useful science information for terrain reconstruction despite its inherent error-prone measurements. The information extracted from Figure 10 used to dictate the minimum number of traverses to achieve maximum error for each navigation strategy was obtained presuming a perfect sensor. In accordance with this prediction from simulation, we are pleased with the RMS error obtained with visual SLAM sensing. Yielding a difference between predicted and actual of 0.0358 m (12%) when navigating according to the traditional lawn mower pattern and

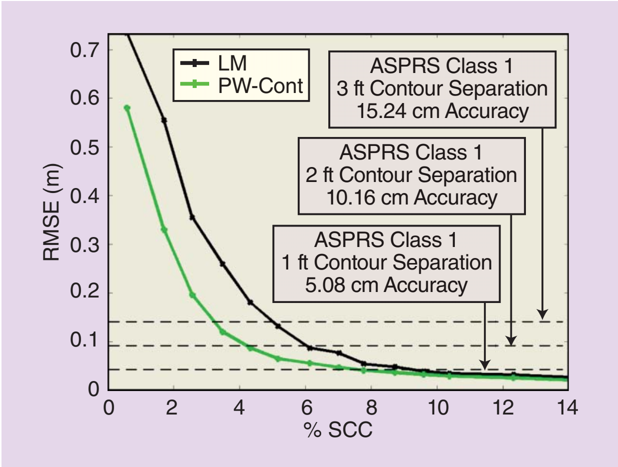

Figure 9. ASPRS standard annotation of average RMS error based on data collected by specific navigation patterns across 100 randomly generated DEMs.

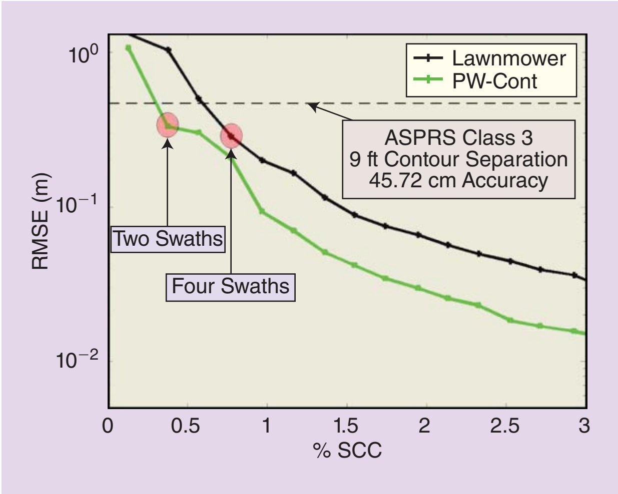

Figure 10. Average reconstruction error annotated with maximum error requirement for Class 3 map for each navigation pattern.

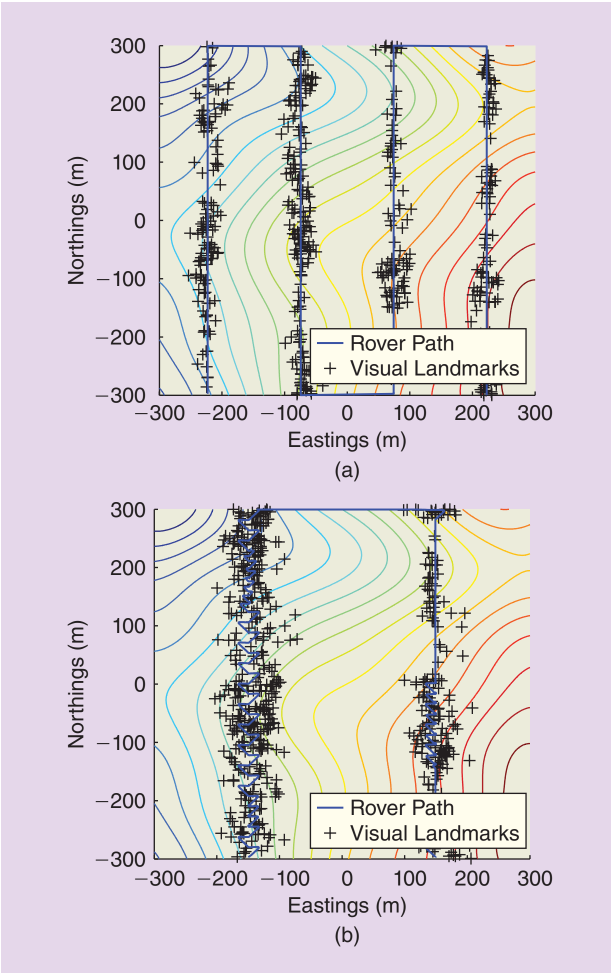

Figure 11. The executed rover paths and an indication of the spatial distribution of the visual landmark for the (a) lawn mower surveying strategy and (b) piecewise continuous surveying strategy.

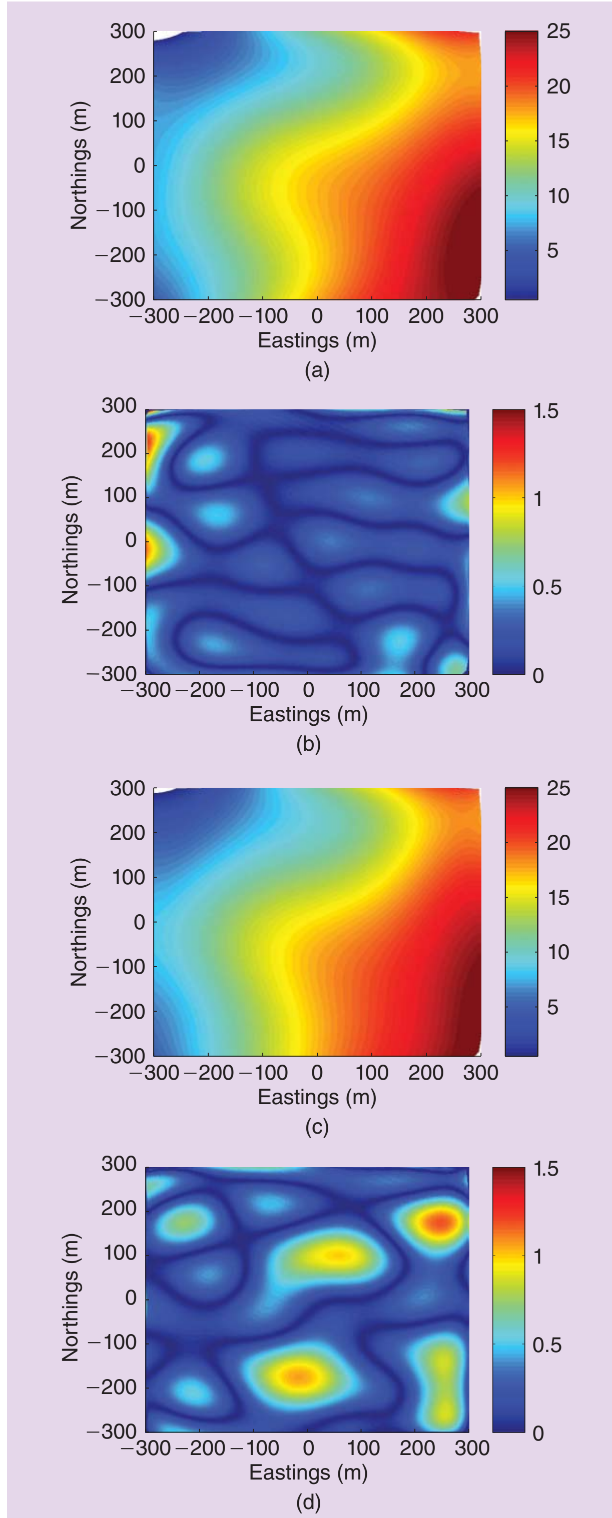

Figure 12. Terrain reconstructions and reconstruction errors using data from (a) lawn mower reconstruction and (b) lawn mower reconstruction error, the lawn mower surveying strategy; and (c) piecewise reconstruction and (d) piecewise reconstruction error, the piecewise continuous surveying strategy.

0.0733 m (22%) when adhering to the piecewise continuous navigation path, both absolute error values meet the desired Class 3 maximum error limit.

The second noticeable item is the importance of the terrain's spatial complexity when selecting one navigation strategy over another. The simple downward-slope feature of our testing terrain reduces the need for spatially diverse paths, where as a test area more analogous to the one shown in Figure 8, typically demands more flexibility in changing navigation directions given the increased presence of hills and valleys.

Conclusions

In this article, we have discussed a methodology for terrain reconstruction of glacier environments based on observed phenomena during a robot traverse. The principle takeaway from our article highlights the significance of augmenting intelligent navigation schemes with environmentally relevant sensing capabilities to comply with desired scientific objectives. Future article will involve applying our approach to observing alternative phenomena, i.e., soil moisture, as well as deploying multiple agents in this field. These field campaigns range from accurately monitoring chemical plumes to providing timely spatial characterization of radiation distribution across an area. We believe that, by coupling robotics with science-based

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objectives such as these, major life-preserving opportunities could continue to be addressed by the robotics community.

Acknowledgments

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TUTORIAL


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The Open Motion Planning Library

By Ioan A. Şucan, Mark Moll, and Lydia E. Kavraki

The open motion planning library (OMPL) is a new library for sampling-based motion planning, which contains implementations of many state-of-the-art planning algorithms. The library is designed in a way that it allows the user to easily solve a variety of complex motion planning problems with minimal input. OMPL facilitates the addition of new motion planning algorithms, and it can be conveniently interfaced with other software components. A simple graphical user interface (GUI) built on top of the library, a number of tutorials, demos, and programming assignments are designed to teach students about sampling-based motion planning. The library is also available for use through Robot Operating System (ROS).

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Motion Planning

Robotic devices are steadily becoming a significant part of our daily lives. Search-and-rescue robots, service robots, surgical robots, and autonomous cars are examples of robots most of us are familiar with. Finding paths (motion plans) efficiently for such robots is critical for a number of real-world applications (Figure 1). For example, in urban search-and-rescue settings, a small robot may need to find paths through rubble and semicollapsed buildings to locate survivors. In domestic settings, it would be useful if a robot could, for example, put away kids' toys, fold the laundry, and load the dishwasher. Motion planning also plays an increasingly important role in robot-assisted surgery. For example, before a flexible needle is inserted or an incision is made, a path can be computed that minimizes the chances of harming vital organs. More generally, motion planning is the problem of finding a continuous path that connects a given start state of a robotic system to a given goal region for that system, such that the path satisfies a set of

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constraints (e.g., collision avoidance, bounded forces, bounded acceleration). This article describes an open source software library for motion planning, designed for research, educational, and industrial applications.

Although most of the work done toward the development of algorithms that solve the motion planning problem comes from robotics and artificial intelligence [1]–[3], the problem can be viewed more abstractly as search in continuous spaces. As such, the applications of motion planning extend beyond robotics to fields such as computational biology [4]–[7] and computer-aided verification [8], among others.

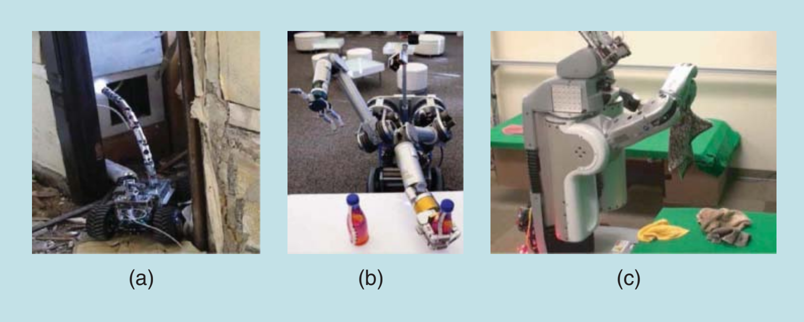

Figure 1. Real-world applications of motion planning. (a) An urban search-and-rescue robot from Carnegie Mellon University's (CMU's) Biorobotics Lab. (b) The HERB robot from CMU's Personal Robotics Lab picking up a bottle. (c) A PR2 robot folding laundry in the University of California at Berkeley's Robotics Learning Lab. Images used with permission from Prof. Choset, Prof. Srinivasa, and Prof. Abbeel, respectively.

Early results have shown the motion planning problem to be PSPACE-complete [9], and existing complete algorithms are difficult to implement and computationally intractable. For this reason, more recent efforts focus on approaches with weaker completeness guarantees. One of these approaches is that of sampling-based motion planning, which has been used successfully to solve difficult planning problems for robots of practical interest. Many sampling-based algorithms are probabilistically complete: a solution will eventually be found with probability one if one exists, but the nonexistence of a solution cannot be reported (see [10]–[13]).

Many of the core concepts in sampling-based motion planning are relatively easy to explain, but implementing sampling-based motion planning algorithms in a generic way is nontrivial. This article describes OMPL (http://ompl.kavrakilab.org), an open source C++ implementation of many sampling-based algorithms (including the Probabilistic Roadmap Method (PRM) [14], Rapidly-expanding Random Trees (RRT) [15], Kinodynamic Planning by Interior-Exterior Cell Exploration (KPIECE) [16], and many more) and the core low-level data structures that are commonly used. OMPL includes Python bindings that expose almost all functionality to Python users. This library is aimed at three different audiences:

- motion planning researchers
- robotics educators
- end users in the robotics industry.

In the following, we will characterize the needs of these different audiences.

Within the robotics community, it is often challenging to demonstrate that a new motion planning algorithm is an improvement over the existing methods, according to certain metrics. First, it is a substantial amount of work for a researcher to implement not only the new algorithm, but also one or more state-of-the-art motion planning algorithms to compare it against. Ideally, implementations of low-level data structures and subroutines used by these algorithms (e.g., proximity data structures) are shared, so that only differences of the high-level algorithm are measured. Second, for an accurate comparison, one needs a known set of benchmark problems. Finally, collecting various performance metrics for several planners with different parameter settings, running on several benchmark problems, and storing them in a way that facilitates easy analysis afterward is a nontrivial task. We, as developers of planning algorithms, have run into the above issues many times. We designed OMPL to help with all these issues, and make it easier to try out new ideas. Moreover, the library is designed in a way that facilitates contributions from other motion planning researchers and provides benchmarking capabilities to easily compare new planners against all other planners implemented in OMPL (see "Benchmarking with OMPL"). We have developed a streamlined process that gives contributing researchers appropriate credit and minimizes the burden of writing code that satisfies our library's application programmers interface (API). At the same time, our aim is to make such contributions easily available to users of OMPL. This is achieved by releasing the code under the Berkeley Software Distribution license (one of the least restrictive open source licenses), releasing frequent updates, and making the code available through a public repository. To foster a community of OMPL users and developers, we have set up a mailing list, a blog, and a Facebook page.

For robotics educators, we have designed a series of exercises or projects around OMPL aimed at undergraduate students. These exercises help students to realize the complexity of motion planning in practice, to develop an understanding of how sampling-based motion planning algorithms work, and to learn evaluation of the performance of planners. We have also designed open-ended projects for undergraduate and graduate students. OMPL is structured to have a clear mapping between the motion planning concepts used in the literature and the classes that are defined in the implementation. The separation between abstract base classes that only specify the interface and derived classes that implement the specified functionality also helps students to understand general concepts in motion planning before focusing on details.

From the beginning, OMPL was intended to be useful in practical applications. This requires that planning algorithms can solve motion planning problems for systems with many degrees of freedom at interactive speeds. An additional requirement is the ability to cleanly integrate OMPL with other software components on a robot, such as perception, kinematics, and control. Through a collaboration with Willow Garage, Menlo Park, California, OMPL is integrated within ROS [17] and serves as the motion planning back-end for the arm planning software stack. The availability of OMPL in ROS makes it easy for end users in the robotics industry to stay up-to-date with advances in sampling-based motion planning.

Background

There has been much work done on both algorithm development and software development for motion planning. This article only discusses aspects pertaining to sampling-based motion planning.

Sampling-Based Motion Planning Definitions

Sampling-based motion planning algorithms relaxed completeness guarantees and demonstrated that many interesting problems can be solved efficiently in practice, despite the theoretically high complexity of the problems [2], [3]. The fundamental idea of sampling-based motion planning is to approximate the connectivity of the search space with a graph structure. The search space is sampled in various ways, and selected samples end up as the vertices of the approximating graph. Edges in the approximating graph denote valid path segments.

There are two key considerations in the construction of the graph approximation: the probability distribution used for sampling states and the strategy for generating edges. An enormous amount of research has been performed toward the development of efficient algorithms that account for these issues [18].

We will not go into the details of various sampling-based motion planning algorithms, as such details can be found elsewhere [2], [3]. Instead, we describe the common components sampling-based algorithms typically depend on, as these relate to the implementations of such algorithms:

- *State Space*: Points in the state space (or configuration space) fully describe the state of the system being planned for. For a free-flying rigid body, the state space consists of all translations and rotations, while for a manipulator with n rotational joints, the state space can be modeled by an n-dimensional torus.
- *Control Space*: A control space represents a parameterization of the space of controls. This is only required for systems with dynamics. For most systems of practical interest, one can think of the control space for a system with m controls simply as a subset of $\mathbb{R}^m$. For geometric planning, no controls are used.
- *Sampler*: A sampler is needed to generate different states from the state space. For control-based systems, a separate sampler is needed for sampling different controls. Some planning algorithms (e.g., [12], [16]) only require a control sampler and do not need a state sampler.
- *State Validity Checker*: A state validity checker is a routine that distinguishes the valid part of the state space from the invalid part of the state space. For example, a state validity checker can check for collisions and whether velocities and accelerations are within certain bounds.

Benchmarking with OMPL

A seemingly simple but often ignored part of motion planning software is benchmarking planning code. OMPL includes benchmarking capabilities (through a class called Benchmark) that can be simply dropped in and applied to existing planning contexts. In very simple terms, a Benchmark object runs a number of planners multiple times on a user-specified planning context. Although simple, this code automatically keeps track of all the used settings and takes all the possible measurements during planning (currently, tens of parameters are recorded for every single motion plan). The recorded information is logged and can be postprocessed using a Python script included with OMPL. The script can produce MySQL databases with all experiment data so that the user can write their own queries later on, but it can also automatically generate plots for all of the performance metrics. For real- and integer-valued measurements, it generates box plots: plots that include information about the median, confidence intervals and outliers. An example is shown in Figure S1. For binary-valued measurements, it generates bar plots. A more elaborate example of what can be done with the Benchmark class can be found at http://plannerarena.org, a Web site currently being developed to establish standard benchmark problems and report performance metrics for various planners on those problems.

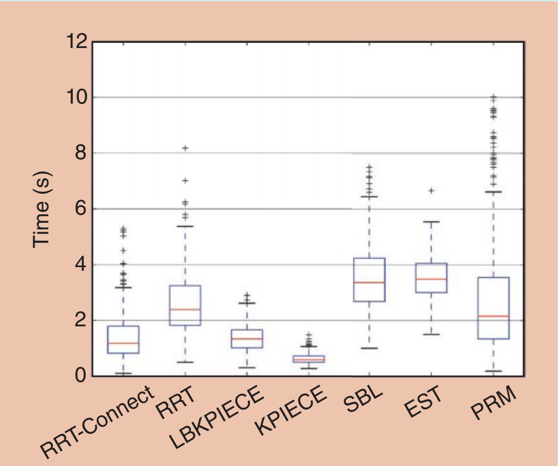

Figure S1. A sample box plot generated by OMPL's benchmark script.

- *Local Planner*: When planning with controls, the local planner is a mean of computing the evolution of the robotic system forward (and sometimes backward) in time. When planning solely under geometric constraints, the local planner often performs interpolation between states in the state space.

Software Packages for Motion Planning

Several other packages for motion planning are available. Some, such as the Motion Strategies Library (MSL, http://msl.cs.uiuc.edu), the Motion Planning Kit (MPK, http://robotics.stanford.edu/~mitul/mpk), and VIZMO++ [19] are no longer maintained. KineoWorks (http://www.kineocam.com) provides commercial motion planning software for academic research and industrial applications. In 2007, our group released the Object-Oriented Programming System for Motion Planning (OOPSMP) [20], which is also no longer maintained.

Another software package that is complementary to OMPL is OpenRAVE [21]. OpenRAVE is open source, actively developed, and it is widely used. It is important to understand the difference in design philosophy behind OMPL and OpenRAVE. OpenRAVE is designed to be a complete package for robotics. It includes, among other things, geometry representation, collision checking, grasp planning, forward and inverse kinematics for several robots, controllers, motion planning algorithms, simulated sensors, and visualization tools. OMPL, on the other hand, was designed to focus completely on sampling-based motion planning with a clear mapping between theoretical concepts in the literature and abstract classes in the implementation. This high level of abstraction makes it easy to integrate OMPL with a variety of front-ends and other libraries. Some integration examples are described in section describing the integration with other robotics software. To some extent, the integration with ROS [17] gives a user many of OpenRAVE's features that are purposefully not included in OMPL. It may also be possible to use OMPL as a motion planning plug-in in OpenRAVE. As a result of the narrower focus in OMPL, we have been spending more resources on implementing a much broader variety of sampling-based algorithms than what is currently available in OpenRAVE, as well as benchmarking capabilities to facilitate a thorough comparison of existing and future sampling-based motion planners.

Relationship with Other Robotics Software

There have also been many efforts to create robot simulators such as Player/Stage [22], Player/Gazebo [23], Webots [24], and MORSE [25]. Microsoft Robotics Developer Studio [26] also contains a robot simulator. Typically, such simulators do not include motion planning algorithms, but they can provide a controlled simulated environment to test motion planners in various environments, on various robots with different sensing and communication capabilities. They often simulate the dynamics of the world (including the robots themselves) using physics engines such as Bullet (http://bulletphysics.org) and the open dynamics engine (ODE, http://ode.org), among others.

Hardware platforms typically require complex software configurations and use various forms of middleware to accommodate this requirement (e.g., ROS [17], Orocos (http: //www.orocos.org), OpenRTM-aist [27], OPRoS [28], Yarp [29]). Such software systems typically include their own visualization system, collision checking, etc. OMPL fits naturally and easily into such systems as it only provides sampling-based motion planning and its abstract interface should accommodate a variety of low-level implementations.

Many of the core concepts in sampling-based motion planning are relatively easy to explain, but implementing sampling-based motion planning algorithms in a generic way is nontrivial.

Conceptual Overview of OMPL

OMPL is intended for use in research and education, as well as in industry. For this reason, the main design criteria for OMPL were as follows:

1) *Clarity of Concepts*: OMPL was designed to consist of a set of components as indicated in Figure 2, such that each component corresponds to known concepts in sampling-based motion planning.
2) *Efficiency*: OMPL has been implemented entirely in C++ and is thread-safe.
3) *Simple Integration with Other Software Packages*: To facilitate the integration with other software libraries, OMPL offers abstract interfaces that can be implemented by the "host" software package. Furthermore, the dependencies of OMPL are minimal: only the Boost C++ libraries are required. Optionally, OMPL can be compiled with Python bindings, which facilitates integration with Python modules.
4) *Straightforward Integration of External Contributions*: We strive for minimalist API constraints for planning algorithms, so that new contributions can be easily integrated.

As opposed to all other existing motion planning software libraries, OMPL does not include a representation of workspaces or of robots; as a result, it also does not include a collision checker or any means of visualization. OMPL is reduced to only motion planning algorithms. The advantage of this minimalist approach is that it allows us to design a library that can be used for generic search in high-dimensional continuous spaces subject to complex constraints. Instead of defining valid states as collision-free, which would require a specific geometric representation of the environment and robot as well as support for a specific collision

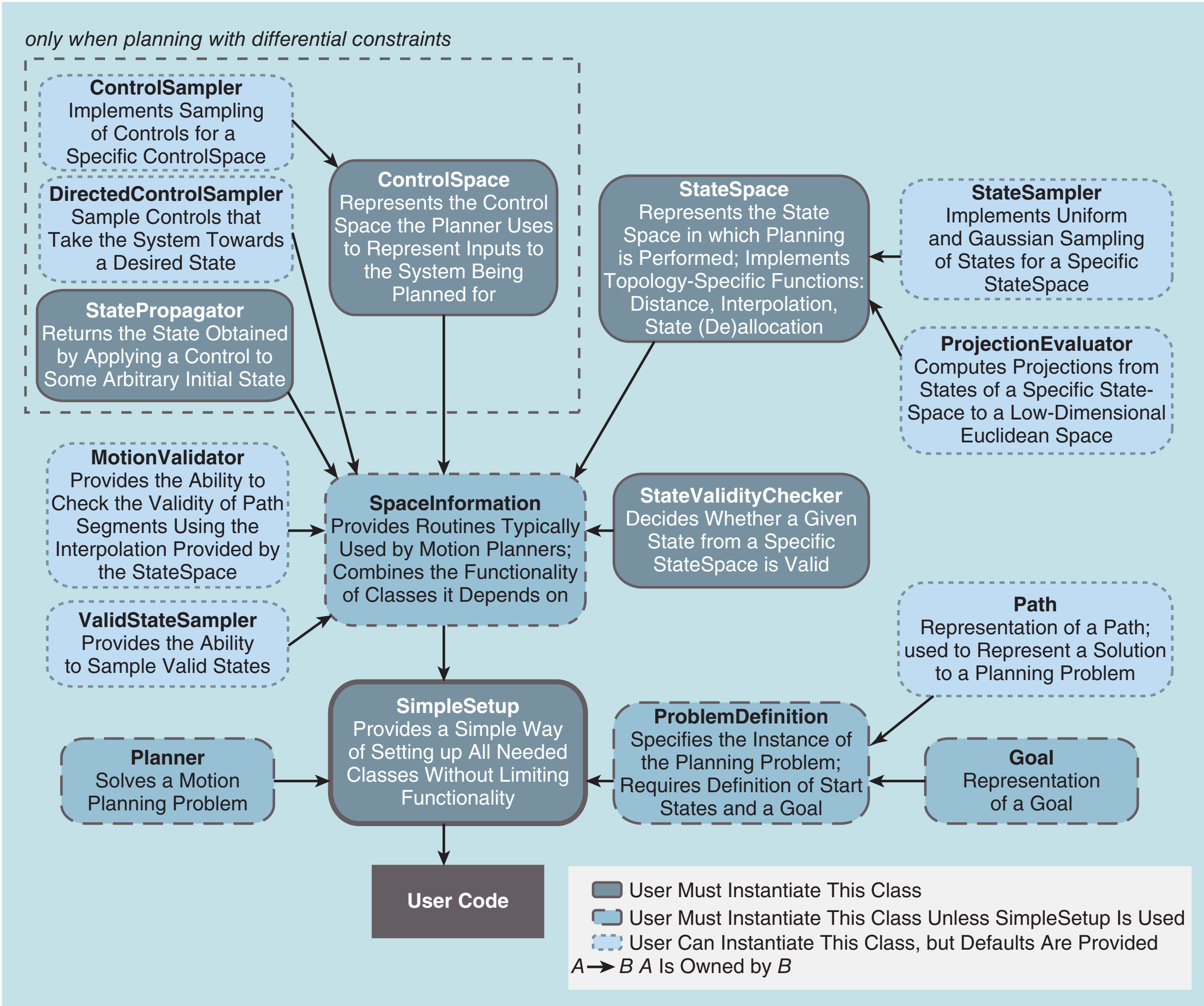

Figure 2. Overview of OMPL structure. Class names correspond to well-understood concepts in sampling-based motion planning. More detailed documentation is available at http://ompl.kavrakilab.org.

checker, OMPL leaves the definition of state validity completely up to the user (or the software package in which OMPL is integrated; see the section about the relationship with other robotics software). This gives the user an enormous design freedom: the user can defer collision checking to a physics engine, write a state sampler that constructs only valid states, or define state validity in completely arbitrary ways that may or may not depend on geometry.

To make OMPL as easy to use as possible, various parameters needed for tuning sampling-based motion planners are automatically computed. The user has the option to override defaults, but that is not a requirement.

Implementation of Core Concepts

In the following we will give an overview of the implementation of the core motion planning concepts in OMPL. Figure 2 gives a high-level overview of the main classes and their relationships. We will use the following notation. Classes are written in a sans-serif font (e.g., StateSpace), while methods and functions are written in a monospaced font [e.g., `isSatisfied()`]. For conciseness, the arguments to methods and functions are omitted.

States, Controls, and Spaces

To maximize the range of application for the included planning algorithms, OMPL represents the search spaces, that is, the state spaces (StateSpace), in a generic way. State spaces include operations on states such as distance evaluation, test for equality, interpolation, as well as memory management for states: (de)allocation and copying. Additionally, each state space has its own storage format for states, which is not exposed outside the implementation of the state space itself. To operate on states, the planning algorithms implemented in OMPL rely only on the generic functionality offered by state spaces. This approach enables planning algorithms in OMPL to be applicable to any state spaces that may be defined, as long as the expected generic functionality is provided.

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Furthermore, OMPL includes a means of combining state spaces using the class CompoundStateSpace. A combined state space implements the functionality of a regular state space on top of the corresponding functionality from the maintained set of state spaces. This allows trivial construction of more complex state spaces from simpler ones. For example SE3StateSpace [the space of rigid body transformations in three-dimensional (3-D)] is just a combination of SO3StateSpace (the space of rotations) and RealVectorStateSpace (the space of translations). Instances of CompoundStateSpace can be constructed at run time, which is necessary for constructing a state space from an input file specification, as is done, for example, in ROS. For a mobile manipulator, one could construct a CompoundStateSpace with the two arms and the mobile base as substate spaces. An arm typically has a number of rotational joints and can be modeled by either a RealVectorStateSpace (if the joints have limits) or a CompoundStateSpace with copies of SO(2). The state space for the base can simply be SE(2) (the space rigid body transformations in the plane).

State spaces optionally include specifications of projections to Euclidean spaces (ProjectionEvaluator). Low-dimensional Euclidean projections are used by several sampling-based planning algorithms (e.g., KPIECE [16], SBL [30], EST [12]) to guide their search for a feasible path, as it is much easier to keep track of coverage (i.e., which areas have been sufficiently explored and which areas should be explored further) in such low-dimensional spaces.

In addition to states and state spaces, some algorithms in OMPL require a means to represent controls. Control spaces (ControlSpace) mirror the structure of state spaces and provide functionality specific to controls, so that planning algorithms can be implemented in a generic way. The only available implementations of control spaces are the Euclidean space and a space for discrete modes, because so far there has not been a need for control spaces with more complex topologies. However, the API allows one to define such control spaces.

State Validation and Propagation

Whether a state is valid or not depends on the planning context. In many cases, state validity simply means that a robot is not in collision with any obstacles, but in general any condition on a state can be used. In OMPL.app (see the section on OMPL.app: A GUI for OMPL) we have predefined a state validity checker for rigid body motion planning. We have also implemented a state validity checker that uses the ODE (see the section on motion planning using a physics engine). If these built-in state validity checkers cannot be used for the system of interest, a user needs to implement their own. Based on a given state validity checker, a default MotionValidator is constructed that checks whether the interpolation between two states at a certain resolution produces states that are all valid. However, it possible to plug in a different MotionValidator. For example, one might want to add support for continuous collision checking, which can adaptively check for collisions and provide exact guarantees for state validity [31].

For planning with controls, a user needs to specify how the system evolves when certain controls are applied for some period of time starting from a given state. This is called state propagation in OMPL. In the simplest case, a state propagator is essentially a lightweight wrapper around a numerical integrator for systems of the form $\dot{q} = f(q, u)$, where q is a state vector and u a vector of controls. To facilitate planning for such systems, we have implemented generic support for ODE solvers and we have integrated Boost.Odeint [32], a new library for solving ODEs. Given a user-provided function that implements $f(q, u)$ for the system of interest, OMPL can plan for such systems. Alternatively, one can use variational integrators [33], or a physics engine to perform state propagation.

Motion Planning Using a Physics Engine

OMPL has built-in support for using the ODE physics engine. Support for other physics engines, such as Bullet, is planned for a future release. We expect that the approach described below can be followed for these physics engines (and others) as well.

The ODE state space consists of the state spaces of the robot and any movable objects in the environment. The user specifies which joints are controlled by the planner and maps those to a ControlSpace. The user can also specify which collisions are allowed (e.g., contact with the support plane) and which ones are not (such as driving into a wall). This simple setup allows one to plan for systems that are difficult to describe with differential equations. The user does not need to worry about all the different possible contact modes that occur when a car drives off a ramp (Figure S2) or when a robot pushes one or more obstacles (Figure S3).

Figure S2. A car-like robot driving off a ramp.

Figure S3. A yellow robot needs to push obstacles to get to its goal.

Samplers

The fundamental operation that sampling-based planners perform is sampling the space that is explored. Additionally, when considering controls in the planning process, sampling controls may be performed as well.

To support sampling functionality, OMPL includes four types of samplers: state space samplers (StateSampler), valid state samplers (ValidStateSampler), control samplers (ControlSampler), and directed control samplers (DirectedControlSampler).

State space samplers are implemented as part of the StateSpace they can sample, since they need to be aware of the structure of the states in that space. For instance, uniformly sampling 3-D orientations is dependent on their parameterization. Three sampling distributions are implemented by every state space sampler: uniform, Gaussian and uniform in the vicinity of a specified point. This first sampler is necessary to sample over the entire space, but the latter two are used for sampling states near a previously generated state. This is the most basic level of sampling.

Within the robotics community, it is often challenging to demonstrate that a new motion planning algorithm is an improvement over the existing methods, according to certain metrics.

Previous work has shown that the strategy used for sampling valid states in the state space significantly influences runtime of many planning algorithms [34]. Valid state samplers provide the interface for implementing different sampling strategies. The probability distribution of these samplers depends on the algorithm used and is not imposed as part of the API. The implementation of valid state samplers relies on the existence of a state space sampler and a state validator (StateValidityChecker). A common approach to constructing valid state samplers is to repeatedly call a state space sampler until the state validator returns true. Several valid state samplers have been implemented in OMPL: for example, a uniform valid state sampler (UniformValidStateSampler), two samplers (GaussianValidStateSampler, ObstacleBasedValidStateSampler) that generate valid samples near invalid ones (which is often helpful in finding paths through narrow passages [35], [36]).

When considering controls in the planning process, a means to generate controls is also necessary. This functionality is attained using control samplers, which are implemented as part of the control spaces (ControlSpace) they represent. Additionally, a notion of direction is also important in some planners: controls that take the system towards a particular state are desired, rather than simply random controls. This functionality is achieved through the use of directed control samplers (derived from the DirectedControlSampler class).

Goal Representations

OMPL uses a hierarchical representation of goals. In the most general case, a Goal can be defined by the `isSatisfied()` function that when given a state, reports whether that state is a goal state or not. While this very general implicit representation is possible, it offers planners indication of how to reach the goal region. For this reason, `isSatisfied()` optionally reports a heuristic distance the goal region, which is not required to be a metric.

GoalRegion is a refinement of the general Goal representation, which explicitly specifies the distance to the goal using a `distanceGoal()` function. The `isSatisfied()` function is then defined to return true when `distanceGoal()` reports distances smaller than a user set threshold. GoalRegion is still a very general representation but allows planners to bias their search towards the goal. A refinement of GoalRegion is GoalSampleableRegion, one which additionally allows drawing samples from the goal region. GoalState and GoalStates are concrete implementations of GoalSampleableRegion.

For practical applications it is often possible to sample the goal region, but the sampling process may be relatively slow (e.g., when using numerical inverse kinematics solvers). For this reason a refinement of GoalStates is defined as well: GoalLazySamples. This refinement continuously draws samples in a separate sampling thread, and allows planners to draw samples from the goal region without waiting, after at least one sample has been produced by the sampling thread.

Planning Algorithms

OMPL includes two types of motion planners: ones that do not consider controls when planning and ones that do. If a planning algorithm can be used to plan both types of motions, with and without controls (e.g., RRT [15]), two separate implementations are provided for that algorithm: one for each type of computed motion. This choice was made for efficiency reasons. With additional levels of abstraction in the implementation, it would have been possible to avoid separate implementations, [20]. The downside would have been that the implementation of planners would have had to follow a strict structure, which makes the implementation of new algorithms more difficult and possibly less efficient.

For purely geometric planning (i.e., controls are not considered), the solution path is constructed from a finite set of segments, and each segment is computed by interpolation between a pair of sampled states (PathGeometric). Several geometric planning algorithms are implemented in OMPL, including KPIECE [16], bidirectional KPIECE, bidirectional lazy KPIECE, RRT [15], RRT-connect [37], lazy RRT, SBL [30], EST [12], and PRM [14]. The lazy variants listed above defer state validity checking in the

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manner described in [38]. In addition, there are multithreaded versions of RRT and SBL.

When controls are considered, the solution path is constructed from a sequence of controls (PathControl). Controlbased planners are typically used when motion plans need to respect differential constraints as well. Several algorithms for planning with differential constraints are implemented in OMPL as well, including KPIECE, SyCLoP [39], EST, and RRT.

An Example

Figure 3 shows the complete code necessary for planning the motion of a rigid body between two states in Python. The corresponding C++ code would look almost identical. The steps taken in the code are: instantiate the space to plan in [SE(3), line 6], create a simple planning context (using SimpleSetup, line 13), specify a function that distinguishes valid states (lines 15 and 16), specify the input start and goal states (lines 18–26), and finally, compute the solution (line 27). The SimpleSetup class initializes instantiations of the core motion planning classes shown in Figure 2 with reasonable defaults, which can be overridden by the user if desired.

Essentially, the execution of the code can be reduced to three simple steps: 1) specify the space in which planning is to be performed, 2) specify what constitutes a valid state, and 3) specify the input start and goal states. Such simple specifications are desirable for many users who simply want motion planning to work without having to select problem-specific parameters, or different sampling strategies, or different planners, etc. This capability is made possible by OMPL's automatic computation of planning parameters. In the example above, a planner is automatically selected based on the specification of the goal and the space to plan in. The selected planner is then automatically configured by computing reasonable default settings that depend on the planning context. If a user decides to choose their own planner, or set their own parameters, OMPL allows the user to do so completely—no parameters are hidden.

```
1  def is StateValid (state):
2      # Some arbitrary condition on the state
3      # (typically collision checking)
4      return state.getX () < .6
5
6  space = SE3StateSpace ()
7  # set the state space bounds
8  bounds = ob.RealVectorBounds (3)
9  bounds.setLow(−1)
10 bounds.setHigh (1)
11 space.setBounds (bounds)
12
13 ss = SimpleSetup (space)
14 # specify user-defined callback function
15 ss.setStateValidityChecker (
16     ob.StateValidityCheckerFn (isStateValid))
17
18 start = State (space)
19 goal = State (space)
20 # we can pick random start states...
21 start.random ()
22 goal.random
23 # ... or set specific values
24 start ().setX (.5)
25
26 ss.set StartAndGoalStates (start, goal)
27 solved = ss.solve (1.0)
28 if solved:
29     print ss.getSolutionPath()
```

Figure 3. Solving a motion planning problem with OMPL in Python. A C++ implementation would look almost identical.

Integration with Other Robotics Software

It is straightforward to integrate OMPL with other robotics software. In the following we will present two case studies that highlight different use cases.

OMPL.app: A GUI for OMPL

We have created a graphical front end for OMPL called OMPL.app. This front end was created for three reasons:

1) to provide novice users (such as students in a robotics class) with an easy-to-use interface to play with several motion planning algorithms and apply them to several example rigid body motion planning problems
2) to demonstrate the integration of OMPL with third-party libraries for collision checking and loading of 3-D meshes, and a GUI toolkit
3) to allow for easy benchmarking of new and existing planners on rigid body motion planning problems using a command line tool (see "Benchmarking with OMPL"). We will go on to elaborate on these reasons.

The graphical interface of OMPL.app is shown in Figure 4. A user can load meshes that represent the environment and a robot, define start and goal states, and click on the "Solve" button to obtain a solution. If a solution is found, it is played back by animating the robot along the found path. By unchecking the "Animate" button, several states along the path are shown simultaneously. It is also possible to show the states that were explored by the

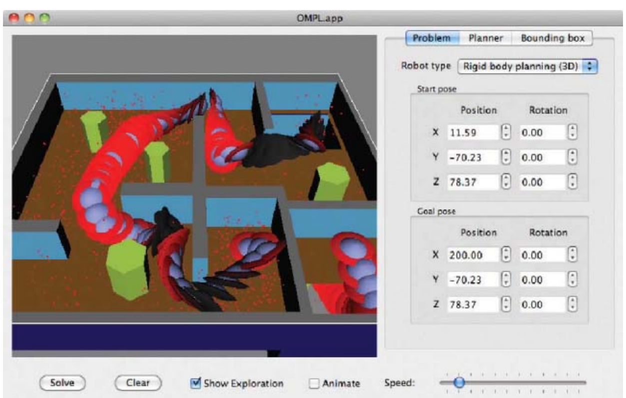

Figure 4. The OMPL.app graphical interface. A solution path for a free-flying UFO robot is shown. Red dots are positions of sampled states.

planner, which can be helpful in tuning planner parameters or selecting the appropriate planning algorithm for a particular problem. By default, the program assumes that a user wants to plan for a free-flying 3-D rigid body [i.e., the state space is SE(3)], but one can also plan in SE(2). We have also predefined a number of common robot types that require controls: a blimp, a quadrotor, a simple kinematic car, a Reeds-Shepp car, a Dubins car, and a second-order car. For each robot type the appropriate planners can be selected in the Planner tab (otherwise, a default one will be automatically selected). Once a planner is chosen, its parameters can be tuned if desired. Finally, the user can adjust the bounding box for the robot's position. By default this is the bounding box of the environment mesh. We have included a number of common benchmark problems, which allow users to develop a basic understanding of which types of problems are hard to solve.

Applications of motion planning extend beyond robotics to fields such as computational biology and computer-aided verification.

The OMPL.app program is also an illustrative example for software developers who want to integrate with third party libraries or their own code. OMPL.app consists of three parts: 1) a C++ library that contains the bindings to third-party libraries, 2) a set of command line demos that highlight significant features of this library, and 3) the GUI itself. The library adds functionality to load meshes in a wide variety of formats using the Open Asset Importer Library (Assimp, http://assimp.sf.net). Users can thus create models of environments and robots in programs such as SolidWorks, 3DS Max, Blender, and SketchUp, and use them in OMPL.app. A large collection of models is also available through the Google 3-D Warehouse. The OMPL.app library also adds collision checking support using the PQP library [40] and FCL library [41]. The internal representation of geometry is decoupled from the graphical rendering, so that the collision checking can also be used in nongraphical applications. The user interface is written completely in Python. The code consists almost completely of creating the user interface elements, connecting them with the appropriate library function calls, and displaying the results.

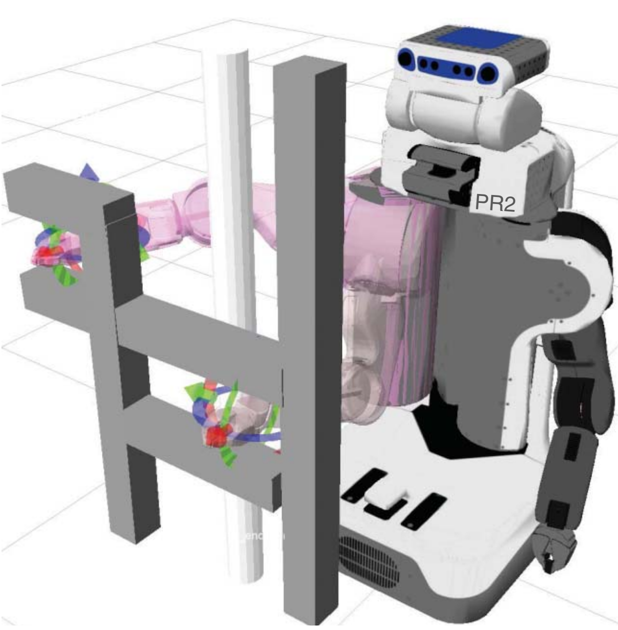

Figure 5. With the ROS rviz visualizer robot poses can be easily configured using OMPL to find feasible paths between poses.

The GUI is also a useful tool to prepare motion planning problems for benchmarking. The GUI can save the complete specification of a problem to a simple text file. The user can then add a list of planner names to this file, along with planner parameter settings, the number of runs per planner, and a time limit for each run, among other data. This configuration file can be given as input to a simple command line program that can perform the actual benchmarking. Usually, the total time required to get statistically significant benchmark results is too long for interactive use for all but the simplest problems, which is why the benchmarking is not directly accessible from the GUI.

It should be relatively straightforward for an experienced programmer to use a different input file parser, a different collision checking library, or different GUI toolkit by mimicking the structure of the OMPL.app library.

Integration with ROS

We expect that many end users in industry and robotics research will use OMPL through its ROS interface. This interface was created by Sachin Chitta and Ioan Şucan, and provides ROS-specific implementations for the abstract base classes OMPL defines. We describe the steps an end-user would need to take to plan motions for a given robot that runs ROS. The PR2 from Willow Garage will be used in the scenario described in the following, but the steps are in fact not specific to the PR2, and apply to any robot that can run ROS.

If a user wants to plan motions for a PR2, they first need to create a model of the geometry and kinematics of the PR2. Within ROS, there is a standard for storing such a model called the unified robot description format (URDF, http://ros.org/wiki/urdf). This XML-based format combines kinematic information with references to files containing meshes of the different robot components. For the PR2 and many other robots, the URDF files already exist (see http://www.ros.org/wiki/Robots). It is often neither desirable nor necessary to plan for all degrees of freedom listed in a URDF file simultaneously. The second step therefore consists of defining one or more groups of joints. Information about the joints to plan for is taken from the URDF and a StateSpace representation for OMPL is constructed. The meshes indicated by the URDF document are used to construct a StateValidityChecker class.

On top of these classes, a `SimpleSetup` class can also be defined, thus making it possible to solve planning problems. The user can also define parameters specific to different planning algorithms, but there is no requirement to do so. A configuration wizard included in ROS can make the setup easier. The third step is to define motion planning problems for the PR2. This can be done in a variety of ways: directly calling planning functions, using ROS-specific APIs, or through visualization tools such as those shown in Figure 5.

Thus, we have described a very basic workflow of planning paths using OMPL in ROS. The ROS-OMPL interface has many more advanced features. First, motion planning problems do not necessarily need to be specified by the user, but can be specified programmatically (e.g., as part of a sense-plan-act loop in conjunction with other components in ROS). Second, different types of state space parameterizations are possible: 1) joint-space representations of the robot, where the robot's degrees of freedom are compounded into different state spaces: $\mathbf{R}^n$ for sequences of single degree of freedom joints with joint limits, *SO*(2) for continuous joints, *SE*(2) for robots moving in plane and *SE*(3) for robots moving in space, and 2) work-space representations of the robot, where for example, the pose of an arm's end-effector is represented as an *SE*(3) state, and the interpolation capability of the *SE*(3) state space is overridden to use inverse kinematics. Third, the ROS interface allows the user to specify complex constraints such as keeping transported objects upright or keeping them within view. Generating states that are in the desired goal region is done in parallel with the execution of the rest of the planning algorithm. The interface also automatically incorporates the geometry of attached objects during planning by attaching carried objects to the kinematic model of the robot.

The ROS interface to OMPL allows users to interact with motion planners in a simple manner. Only the set of joints the user wants to plan for (usually grouped and referred to by the name of the group) and a specification of the goal are needed. The goal can be specified, for example, as a bounding box in the joint space, or a desired link pose. We believe that this functionality will allow for the widespread use of OMPL in a broad variety of settings.

Discussion

We have described OMPL, an open source general-purpose library for sampling-based motion planning. Thanks to its integration with ROS, it can be used on a wide variety of hardware platforms, and currently serves as the motion planning back end for the ROS manipulation software stack (also known as MoveIt! in future releases of ROS [42]). However, OMPL does not depend on ROS, and can be used independently. OMPL.app includes a graphical front end for OMPL and serves as an example of how OMPL can be integrated with third-party libraries.

One of the target applications of OMPL is in robotics education. The graphical front end provides a gentle introduction to the complexity of motion planning: without writing any code, students can solve motion planning problems using different planners, vary the parameters used for planning, and perform extensive benchmarking experiments. Through many demo programs and tutorials, students should get quickly up to speed and develop new planning algorithms or alternate implementations of abstract APIs.

The ROS interface to OMPL allows users to interact with motion planners in a simple manner.

We encourage contributions from other researchers. In fact, we are already working with other research groups on incorporating their algorithms into OMPL. Within our own group, OMPL has proven to be useful for performing conformational search for macromolecular ensembles. Here, its generality has paid off significantly. We can use Rosetta—a standard molecular modeling package—to create a new state space for molecules, and use Rosetta's sampling capabilities while performing a search for biophysically plausible configurations of molecules using OMPL.

Long-term success depends on adoption and support by the robotics community. Through continued development in our group and contributions from others, we expect OMPL to become a very useful tool for motion planning researchers, users in the robotics industry, and students who want to learn more about sampling-based motion planning.

Acknowledgments

This work was supported in part by Willow Garage and NSF CCLI under Grant DUE 0920721 and Grant IIS 0713623. Willow Garage was instrumental in initiating and supporting this effort. The development of OMPL has also benefited from previous efforts by the Kavraki Laboratory at Rice University to develop a motion planning software package, in particular OOPSMP. We are indebted to all other Kavraki Laboratory members, past and present, for providing code, inspiration, and feedback. Previous work by Erion Plaku, Kostas Bekris, and Andrew Ladd in particular has been influential in the design of OMPL. The authors would also like to thank Sachin Chitta and Gil Jones from Willow Garage for the development of the ROS bindings for OMPL and helpful discussions.

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At the End of a Great Year: Listen to the Voice of Young Roboticists

By Laura Margheri, the RAS-SAC Chair 2012–2013

The end of 2012 is approaching and the Student Activities Committee (SAC), with your help and support, has remained a large and active community. I am very happy to report that the number of students in our Society has been continuously growing and has nearly doubled from 2009 to 2011.

Many of you have enjoyed the SAC-organized events held in conjunction with the IEEE International Conference on Robotics and Automation, the IEEE/RSJ International Conference on Intelligent Robots and Systems, and the IEEE RAS/Engineering in Medicine and Biology Society International Conference on Biomedical Robotics and Biomechatronics this year. Again, I want to thank all the students, senior researchers, and professors for their support and participation in these events as well as their efforts to encourage and expand students' interests. These events are extremely valuable resources for our career growth and allow us to learn through meeting and interacting with the leaders of academia and industry. We plan to continue with similar events during the next year and we hope that you will show your support and participate, and we welcome suggestions for further improvement.

Welcome to the Student Activities Committee Interview Corner: current projects, vision, and challenges of robotics students and leaders.

The primary SAC activities are usually organized in parallel with conferences, when students have the chance to meet face-to-face with robotics leaders.

The opportunity to discuss research activities and to network, however, exists in other ways, and attending conference is not always possible for students. Therefore, in the year ahead, we will promote additional ways for students to share their work and increase their visibility in the robotics and automation community.

The new RAS Web site, the Facebook page, and the students Interview Corner (please see below) are only some examples. The Student Activities Committee is always ready to help all fervent inventors to share their activities, encourage innovative ideas, and advise on their career, and you are always more than welcome to contact us to candidate for the interview, propose initiatives, give us your feedback, or ask any questions.

Have a great, successful and peaceful New Year.

Interview Corner

Surgical robotics clearly represents a field where research has the possibility to lead to industrial exploitation, and in this first Interview Corner, we asked Selene Tognarelli and Giuseppe Tortora from the BioRobotics Institute (Scuola Superiore Sant'Anna, Pisa, Italy) to explain their research activity and the goals and ideas of robotic surgery for the future. These two young engineers are working on a visionary, breakthrough medical robotic project, ARAKNES.

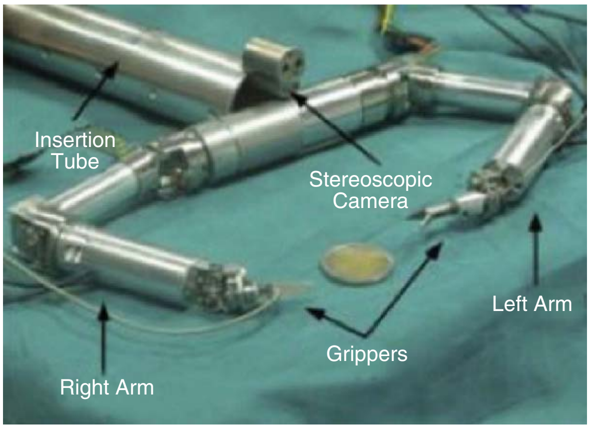

Figure 1. The ARAKNES robot's arms.

Q. What is ARAKNES?

A. The ARAKNES Project is part of the Seventh Framework Programme of the European Commission, and it involves 11 partners from Europe, coordinated by the Scuola Superiore Sant'Anna. The aim of the ARAKNES Project is the development of an innovative robotic platform for scar-less, or even no-scar, surgery.

Q. Who is behind the breakthrough idea of the project?

A. ARAKNES is a complex project born from the idea of visionary scientists,

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Figure 2. The Surgical Robotics team at the BioRobotics Institute.

Prof. Paolo Dario and Prof. Arianna Menciassi. They are the technical coordinators of the project. Supported by one of the most famous European surgeons, Prof. Alfred Cuschieri, ARAKNES provides a close link between innovative technologies and surgical applicability.

And, last but not least, a group of young researchers and Ph.D. students are involved as they look with enthusiasm to the new frontiers of surgical robotics.

Q. What are the distinctive features of the project?

A. The Da Vinci system is a successful example of a surgical robot introducing clear advantages to surgeons. In this case, laparoscopy is still performed in a traditional, yet robot-aided way.

ARAKNES project aims to address abdominal surgery through a new medical approach, the single-port laparoscopy (SPL). SPL can be performed with a compact, dexterous, and less-expensive robot that could be used in the operative room with a shorter setup time. The ARAKNES robot is based on internal and external actuation to move its arms with six degrees-of-freedom and one gripper in a bimanual configuration under stereoscopic vision.

Q. What are the results you achieved?

A. The ARAKNES platform is undergoing experimental validation. Expert surgeons discussed limitations and potentialities of the system after repeated training sessions. Preliminary in vivo experiments also showed the fundamental applicability of the system in real surgery.

Q. How does the new scenario influence the relationship among surgeons, patients, and robots?

A. Human–machine interaction is one of the main aspects to be considered. On the patient's side, the keyword is safety—to present a reliable future alternative to traditional surgery. On the surgeon's side, the keyword is training. We do not want the robot completing the entire job, we want to preserve the leading role of the surgeon. Young surgeons will be trained with the assertion that robotics in surgery is not part of a fantasy issue but mere reality.

Q. In your opinion, what will be the future of surgical robotics look like after ARAKNES?

A. An innovative robotic platform is being developed within the project to transluminally address abdominal surgery through natural orifices with no need of abdominal incisions. Endoluminal and transluminal robotic techniques will be the future trend of medical practice for addressing common diseases after early diagnosis.

For more information visit www.araknes.org.

Contacts: s.tognarelli@sssup.it, g.tortora@sssup.it.

Pitfalls of Publications: On the Sensitive Issue of Plagiarism

By Ludo Visser, Tamás Haidegger, and Nikolaos Papanikolopoulos

"Plagiarism is the practice of taking someone else's work or ideas and passing them off as one's own."

—New Oxford American Dictionary

"Plagiarism means to steal and pass off (the ideas or words of another) as one's own. To use (another's production) without crediting the source."

—Merriam–Webster Dictionary

IEEE defines plagiarism as "the use of someone else's prior ideas, processes, results, or words without explicitly acknowledging the original author and source" [1].

At first, this may appear to give a concise definition of plagiarism and a clear understanding why it is wrong; however, in practice, plagiarism is one of the most complex ethical issues scientists and engineers face in connection with publishing and publications. Despite some obvious cases, boundaries between referencing, quoting, adopting, and copying are not so clear. Some recent scandals (e.g., the case of the editor-at-large of *Time* and CNN host Fareed Zakaria, the resignation of the German defense minister, the Hungarian president, or the Indonesian professor with a degree from Flinders University) have made clear that plagiarism is a serious issue. In fact, due to digital technology (i.e., easy access and "copy and paste" ability), plagiarism is becoming an increasingly large problem for publishers that requires delicate handling [2]. Recent conference surveys show an average of a dozen cases per robotics conference, and numerous cases have been initiated against authors for academic misconduct.

According to IEEE, "plagiarism in any form is unacceptable and is considered a serious breach of professional conduct, with potentially severe ethical and legal consequences" [1]. Consequently, IEEE started to impose severe punishment upon those who commit deliberate acts of plagiarism, including titles being revoked and authors being banned from publishing. In addition, publishers are struggling to deal with the malpractice of self-plagiarism, which concerns the somewhat vague concept of copying one's own work. While this is a topic of ongoing debate, self-plagiarism is an issue for publishers because it affects copyrights and the quality of their publications.

The peer-review process is the first line of defense against plagiarism and it is therefore important to raise awareness among students and professionals, in academia and industry. Reviewers might come across cases of plagiarism while reading through manuscripts, reports, or proposals, so it is important that they know how to recognize such cases and how to deal with them.

Within the Student Reviewer Program (SRP) [3], we exert an effort to train young researchers in the "art of reviewing," and introduce them to the reviewing process in a controlled and supervised way. Within this context, it is important that the spotlight is also directed onto delicate issues within the reviewing community. Therefore, in this article, we discuss some key issues regarding plagiarism and self-plagiarism and give insights into the approach that is taken within IEEE. Furthermore, we provide some useful tools and techniques to identify cases of plagiarism. Hopefully, this will lead to a better understanding and higher awareness of the practice, particularly among reviewers.

Plagiarism In and Out

In the broadest sense of the definition, plagiarism is copying someone else's work. However, there are many intricate details involved.

First of all, copying a work can be done in many ways. The most obvious is to literally copy (parts of) a manuscript and submit them as one's own. However, in most cases, it is by far not that obvious. Instead of literally copying text, words and phrases may be translated from another language, altered to reflect the individual's writing style, or embedded into the author's own work. Furthermore, on a more abstract level, ideas and concepts may also be plagiarized. Analogous to patent infringement, this can include taking intellectual material and wrongfully presenting it as one's own, either an idea as a whole or in parts, or building forth on someone else's work without proper referencing or licensing.

Definitions get even more fuzzy when we take a look at the concept of self-plagiarism. In short, self-plagiarism means that a person publishes a work or an idea that has already been published in the past but claims it as new.

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This can also include improper quoting and referencing of previous works. The ethical boundary is undefined, since it is not uncommon to reuse (paraphrase) parts of a previous publication to a new one.

Legally speaking, we have to distinguish two cases:
1) an author signs off the copyright of the entire work to the publisher when a manuscript is accepted for publication
2) the copyright stays with the author.

In the first case, reusing parts of the work for a new publication can be unlawful if the new article is submitted to a different publisher, but exploring in depth (and trying to exploit) the differences between copyright agreements is not within the scope of this article. In the second case, reusing (parts of) the work would be a discussion of ethics and professionalism. The entire field is just determining its standards and best practices along these lines.

Ethically speaking, self-plagiarism is often encountered within the process of "evolutionary publishing." This is an accepted (although sometimes contested) practice of publication where the initial results are submitted to a workshop, then extended to a full conference paper that may become a journal article or a book chapter. This approach of building on previous publications is clearly a source of possible unethical cases of self-plagiarism.

Self-plagiarism is the subject of continuous discussion at all levels of the research community, with many arguing that self-plagiarism is a contradiction in terms, since you cannot really steal from yourself. Conferences typically require an author to explicitly state that the material being submitted is new, the author's own work, and has not been published before. Whether or not one acknowledges that self-plagiarism is unethical or being prohibited by copyright agreements, reuse of large portions of previous works negatively affects the quality and contributing value of publications, and, eventually, entire conferences in particular.

Understanding (Self-) Plagiarism

To entirely understand the issue of (self-)plagiarism, possible motivations should be identified. Researchers and scientists (in most countries) are evaluated on the basis of the number of their publications, which has evolved into an important metric for assessing scientific merit. A consequence of this is publishing more and more for the sake of quantity, where quality takes second place.

Sometimes, this results in cases of blatant copies of the works of others, with the only aim to obtain high-impact publications or finishing a dissertation (e.g., Pal Schmidt, the Hungarian ex-president, even copied factual mistakes into his doctoral thesis). This pressure may lead to sloppiness, when relevant works are not always cited properly or altogether overlooked. Further lays the practice of incremental publishing, when results are reported in subsequent events and periodicals. While this is not unethical per se, the tendency to (over-)publish even the smallest results obviously leads to large overlaps between incremental papers, which might fall into the category of self-plagiarism. Also, since these incremental works are typically submitted to lower ranked journals and conferences where the peer review procedure is less rigorous, there is a smaller chance that they are caught and prevented from (re-)publication.

It is clear that the competitiveness in present day research is a leading cause of plagiarism. Although it does not justify it, it can make it understandable why it happens. Since the scientific world is likely not to change anytime soon in terms of funding principles and competition, it is important to realize that plagiarism is indeed an issue which will become a bigger issue as scientific competition grows, and that we need to learn how to deal with it.

In this process, the role of the scientific advisor/mentor is critical. Showing students what is acceptable is important, and examples of plagiarism could help in explaining the limits. However, many times advisors are surprised to find out the extent of plagiarism in their advisees' work, thus it is too late to address the problem at that stage.

Dealing with Cases of Plagiarism

The next step is to identify plagiarism, and the peer-review process is the most important tool for that. Unfortunately, there is no fail-safe way to identify plagiarism, but looking at the definitions already suggests where to start.

Sometimes it is quite obvious. If parts of a text are directly copied into a manuscript, the writing style (or even the font) may not match the style of the rest of the paper. This is probably the best indicator that something might be fishy. There is a substantial set of specialized software tools that can help in finding the original documents that contain the suspicious text. The IEEE Robotics and Automation Society (RAS) started to screen papers in 2011. The software tools were first used in conferences and eventually deployed to the transactions. For example, at the IEEE International Conference on Robotics and Automation (ICRA), the iThenticate software [4] is used to filter out possible cases of plagiarism. The software generates a report that highlights the overlaps between a given paper and other sources (including both the public domain of the Internet and reference databases) from which the text has been taken. Further, it provides an overlap score, which may be compared to a threshold. Although the software often gets confused by prior technical reports or common references, it is effective in general, and its cost for a conference like IEEE ICRA is only in the order of a couple of hundred dollars.

However, as outlined above, many abusers edit the text to more closely match their own writing style, and text recognition software will likely fail in such cases. It may still happen that a reviewer recognizes his or her own work being paraphrased. However, more often it comes down to their expertise in the research field to recognize plagiarism.

The situation is very similar for figures. Authors tend to believe that any figure or illustration found on the Internet may be freely used in publications. In reality, most of those images and charts are copyrighted, despite that fact that they are widely used and reprinted without proper referencing. Journals often require an individual confirmation of copyright for every figure in an article. Depending on the publisher's contract, authors may be able to acquire an official permission for reprinting their own materials; however, the charges for copyrighted figures can rise very high (depending on the target audience of the reprint, the number of copies, and the affiliation of the author). The best advice for authors is to invest effort in identifying the copyright owner of a figure, and, even in the case where images are downloaded from the Internet, ask for a written permission from the source and insert appropriate credits in the caption. If a reviewer is having concerns about the originality of a figure in a manuscript, Google's image finder provides an easy way to search the Internet for similar figures (just drag and drop the image into the query text box).

Spotting the Copycats

There is no definite checklist that can be used for recognizing plagiarism, but good indicators are as follows:

- lack of references and citations, or the over-representation of the author's own publications in the reference list
- outdated references, suggesting that no recent research/literature review was done
- figures that do not match with other figures in style, or are of very low quality
- unusual, bold statements about the generic status of the field and its future
- sudden changes in the writing style between consecutive paragraphs.

Once a reviewer suspects a case of plagiarism, the most important thing is to report their concerns to the liaison editors, providing references to the original works as proof. Then, the liaison editors will take a proper action. IEEE guidelines provide a protocol for how to deal with plagiarism [5]; in particular, the following should be considered:

- amount of text being plagiarized (ranging from a single sentence to a full paper)
- proper use of quotation marks
- appropriateness credit notices
- properness of paraphrased text.

The guidelines identify five levels of plagiarism, according to severity.

- Level 1 pertains to the uncredited verbatim copying of a full paper, or the verbatim copying of a major portion (>50%), or verbatim copying within more than one paper by the same author(s).
- Level 2 pertains to the uncredited verbatim copying of a large portion (between 20% and 50%) or verbatim copying within more than one paper by the same author(s).
- Level 3 pertains to the uncredited verbatim copying of individual elements (paragraph(s), sentence(s), illustration(s), etc.) resulting in a significant portion (<20%) within a paper.
- Level 4 pertains to uncredited or improper paraphrasing of pages or paragraphs.
- Level 5 pertains to the credited verbatim copying of a major portion of a paper without clear delineation (e.g., quotes or indents). [6]

The measures taken by IEEE against the author(s) depend on the severity level, and therefore it is very important that proof is provided enabling fair judgment of the case.

Discussion

Within publications of IEEE RAS, several cases have been discovered, and at every event a handful of very serious cases have been encountered. An ethics committee has been set up within RAS to facilitate the evaluation of these cases. The committee makes a recommendation to the vice-president for conference activities (a position currently held by Prof. Nikolaos Papanikolopoulos), who then presents the cases to the IEEE headquarters. Numerous authors have been banned from publishing in IEEE because of plagiarism issues, and the pressure is mounting to increase the sanctions. This clearly illustrates the severity and actuality of the issue. Furthermore, it is absolutely necessary to raise awareness and educate (prospective) authors on this issue.

A second part of the discussion pertains to penalizing authors who have plagiarized work. A common problem is how to assess the responsibility of the various authors. In some cases, the advisor blames the student authors, and finding the key individual responsible for the plagiarism is almost impossible. Assuming that the responsible authors can be identified, an open question still remains in how they should be penalized.

> Journals often require an individual confirmation of copyright for every figure in an article.

The SRP is committed to educating young researchers on these topics and battling the problem. We believe that this article contributes to raise awareness on the issue of plagiarism, and that is can start new discussions among researchers and scientists.

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ON THE SHELF

Five Hundred and Seven Mechanical Movements

By Henry T. Brown

Five Hundred and Seven Mechanical Movements is a classic little jewel of moving mechanisms, a valuable resource for anyone who is building robots. When first published in 1868, this book offered the pre-Internet world a collection of the greatest moving devices of the time, gathered together in one small readable volume. Reissued in 1995, this book is still being used and enjoyed. Although there is a great deal of innovation happening now in software, every robot that has to act in the world requires mechanisms, and this book provides them.

You will find reading this book enjoyable, if just for its historical value alone. In fact, you don't have to have a technical background to understand the descriptions, although it will remind those with engineering backgrounds of school-days learning and provide innovative variations that might not have been thought of. On the historical side, the book includes the latest discoveries of the time, such as C.R. Otis's safety stop for the elevator and Pickering's governor for a steam engine.

However, the book also has a great deal of useful information for the robotics field. It includes 507 clearly labeled and numbered pictures that correspond to the numbered descriptions of many of the important mechanisms used in robot construction. Each mechanism is clearly drawn, illustrating how the parts fit together. Then, the picture's description explains how the mechanism works and also tells what kind of motion is produced. This method of organizing lends itself well to be used as a quick reference or inspiration during the design process.

Some examples of the many types of mechanisms you will find are brakes, blowers, cams, compasses, couplings, cranks, differential movements, ejectors, engines, escapements, gauges, gearing, governors, gyroscopes, various types of hammers, hydraulics, hooks, ladders, levels, pantographs, pendulums, pinions, presses, pulleys, pumps, rack and pinions, ratchets, regulators, rollers, screws, shears, stops, toggles, wheels, windlasses, and wipers—to name just a few!

As some examples of the level of detail included, there are 23 different kinds of pulleys, each providing a unique solution to a particular kind of pulley movement you might need. The gear section is quite detailed, with many varieties for circular motion, such as transmission of circular motion, reciprocating motion, planetary motion, clutch boxes, and transmitting different speeds. Each of the categories listed above includes multiple variations, so that you can find a very specific design.

The book gives a few simple numerical calculation methods at times, but math is not emphasized. The real value of this book is in seeing the clear drawings and reading the precise explanations of exactly how motion is expressed by each type of mechanism. You will find solutions to meet the many kinds of movement situations you need for your robot thanks to all of the fine-grained variations this book includes. And in the process of enjoying a journey through history, you just might find the creative solution you are looking for. We highly recommend this practical and fun little book!

—Reviewed by C. Alexander Simpkins, Ph.D., and Annellen M. Simpkins, Ph.D., San Diego, California

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Design and Control of Intelligent Robotic Systems

Edited by Dikai Liu, Lingfeng Wang, and Kay Chen Tan

Design and Control of Intelligent Robotic Systems is an edited collection of advanced research in robotics, part of the series *Studies in Computational Intelligence*. Robotics is a young field. The advent of inexpensive powerful computation, sensors, actuators, and more powerful CAD/analysis packages is opening doors that were previously far beyond reach. More effective theories and strategies are being rapidly developed, as increasingly challenging and complex problems are identified and addressed. This book series is an attempt to gather together and present the newest work; this volume emphasizes the design and control of robots.

The book is composed of 21 chapters, with topics ranging from an overview of computational intelligence, various swarm optimizations for groups of robots, behavioral learning methods, path planning inspired by emotional intelligence, heterogeneous systems, and acquisition of neural structure, to the design and control of a rehabilitation robot (to list a few of the many topics). The book is well written, clearly laid out, and informative.

Each chapter is quite different and self contained, and so it is not

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possible to cover all the topics in this review. However, I will highlight a few interesting points. The first is that a number of techniques are presented that address the issue of increasing complexity in robotic systems—currently a significant problem. Some of these include particle swarm optimization, (EV) evolutionary, neural, fuzzy, MRAC (model reference adaptive control), and hierarchical approaches. In addition, not only does the book cover the design of fixed control algorithms, but it also includes how to adapt the algorithm for unstructured or uncertain environments and changing task parameters (hence, "intelligent" in the book title). This can be achieved by incorporating learning methods (several of the above methods incorporate some adaptation or learning components) that alter the parameters of the controller in some useful way (i.e., optimizing by minimizing cost, by altering weights to improve some performance criterion, or by changing the very structure of the system).

Though the book is a collection, not a textbook, the commonalities of the theme make it a useful read for robotics researchers, graduate students, or individuals interested in familiarizing themselves with the latest in a range of robotics research topics, centered around the concepts of design and control. More focus is given to the control and algorithmic side than to the design of physical systems, but most of the chapters are applied to physical systems in well-described experiments.

One especially useful component for those interested in going beyond the book is the reference section at the end of each chapter. By the end of the book, the reader will definitely be better informed about the newest research in intelligent robotics, methods, and the many nuances of implementation. Since robotics typically involves not just purely theoretical exercises, this difficult-to-strike balance between theory and implementation is significant. I recommend this book to anyone interested in expanding his or her repertoire of techniques. Those who are already familiar with the techniques in this book will not only deepen their understanding of the methods themselves, but also how to address the nontrivial challenges of implementation.

—Reviewed by C. Alex Simpkins, Jr., Ph.D., Seattle, Washington

European Commission, Industry, and Academia Commit to Bigger and Better Robotics Sector

By Bruno Siciliano

The European robotics community has promoted the foundation of euRobotics aisbl [1], a nonprofit international association for all stakeholders in European robotics. The goal of euRobotics is to build upon and continue successful cooperation between the members of the two European community-driven networks from industry (European Robotics Technology Platform EUROP [2]) and academia (European Robotics Research Network EURON [3]), and lead to the sustainable development of the European robotics community as only one organization. One of its main missions is to collaborate with the European Commission (EC) to develop and implement a strategy and a roadmap for research, technological development, and innovation in robotics, in view of the launch of the next framework program Horizon 2020 [4]. Thirty-five founding member institutions from industry and academia signed the statutes of the association in Brussels on 17 September 2012 (see Figure 1).

Robotics is a key driver for Europe's growth and competitiveness.

The association has been nurtured by the partners of euRobotics [5], a coordination action funded by the EC under FP7, which was started in January 2010 and will end in December 2012.

The objectives of euRobotics are to boost European robotics research, development, and innovation and to foster a positive perception of robotics. It aims at

- strengthening competitiveness and ensuring industrial leadership of manufacturers, providers and end users of robotics technology-based systems and services
- providing the widest and best uptake of robotics technologies and services for professional and private use
- improving the excellence of the science base of European robotics.

To reach its objectives, euRobotics has agreed with the EC to prepare the launch of a public–private partnership (PPP) in robotics, to help Europe-based companies take a larger share of the €15.5 billion annual global robotics market, as well as to create new companies. The day after the founding of euRobotics, its president, Dr. Bernd Liepert (chief technology officer of KUKA AG), together with the vice president for research, Prof. Herman Bruyninckx (KU Leuven), and the vice president for industry, Dr. Rainer Bischoff (KUKA Laboratories), joined EC Vice President Neelie Kroes, commissioner for the digital agenda, in signing a memorandum of understanding, the first step towards a PPP launch in 2013 (see Figure 2). The Commission believes that the future PPP will strengthen the EU robotics sector.

Robotics is a key driver for Europe's growth and competitiveness. Three million jobs are created or maintained worldwide as a result of using one million industrial robots. Europe's robotics industry is highly successful, accounting for about a quarter of global production in industrial robots and a 50% market share in professional service robots. The domestic and professional service robot markets are expected to grow by 40% in the coming years, with the strongest growth occurring in rescue, security, and professional cleaning applications. By 2020, service robotics could reach a market volume of more than €100 billion per year. The PPP in robotics aims to

1) develop strategic goals for European robotics and foster their implementation
2) improve the industrial competitiveness of Europe through innovative robotic technologies
3) position robotic products and services as key enablers to help solve Europe's societal challenges
4) strengthen the networking activities of the European robotics community
5) promote European robotics
6) reach out to existing and new users and markets
7) contribute to policy development and address ethical, legal, and societal issues.

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Figure 1. Representatives of the member institutions of euRobotics aisbl in the hall of the Diamant Building in Brussels, the registered office of the association.

The private partners in the PPP (from academia and industry) will now prepare a proposal for the PPP for the Commission to examine and formally endorse.

The EC has funded more than 120 robotics research projects [6] with around €600 million in the last five years. They address topics such as scene and situation understanding, perceiving the world through artificial senses (computer vision, haptics, etc.), and physical behavior such as grasping objects or locomotion in everyday spaces. The global demand for robots and robot-related products was worth around €15.5 billion in 2010, including around €3 billion in Europe.

A recent Eurobarometer study on robotics [7] revealed that more than two-thirds of EU citizens (70%) have a positive view of robots; a majority agree that robots "are necessary as they can do jobs that are too hard or too dangerous for people" (88%) and that "they are a good thing for society because they help people" (76%).

The EC also supports robotics research through its research and innovation framework funding programs. The European Parliament and Council are currently discussing the Commission's proposal for Horizon 2020. Running from 2014 to 2020, with an indicative €80 billion budget, the program is part of the drive to create new growth and jobs in Europe. Boosting and focusing the EU's research, development and innovation efforts are key elements of the digital agenda for Europe.

Figure 2. From left, to right: Neelie Kroes, Bernd Liepert, Rainer Bischoff, and Herman Bruyninckx, toasting after the signature of the memorandum of understanding for the launch of a PPP in robotics.

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The 2012 IEEE Robotics and Automation Society (RAS) Safety, Security, and Rescue Robotics (SSRR) Summer School

By Raymond Sheh and Haldun Komsuoğlu

SSRR: for the Dissemination of the Challenges and Best-in-Class Capabilities

In recent years, robots have been used increasingly to respond to natural disasters, industrial accidents, and terrorist incidents to avoid putting human lives on the line. The 2012 IEEE Robotics and Automation Society (RAS) Safety, Security, and Rescue Robotics (SSRR) summer school is a dissemination and networking event that aims to propel the development of technologies that make a real difference in first-response situations.

More than a purely academic exercise, the Summer School pushed the boundaries in response robotics through collaboration among a selected group of 58 students, first responders, researchers, representatives of manufacturers, and representatives of standards organizations to promote the identification and dissemination of real needs, realistic development goals, and best-in-class capabilities. DHS-NIST-ASTM International standard test methods were used as the common language to enable structured exchanges between these groups. This event also had a very strong hands-on learning and experimentation component.

The goal is to have attendees not only leave with a better understanding of the best-in-class implementations and a starting point or point of comparison for their own research, but they should also have contributed to an ongoing, open body of work that other researchers in the wider SSRR community can build on. In the process, it is hoped that the event generates long-term partnerships and collaborations across different groups, countries, disciplines, and communities.

Turkey was selected as the host country because of its immediate need for effective first-response technologies. Located on two major fault lines, Turkey, with its diverse geology, is a country that frequently suffers from a wide variety of natural disasters. Sadly, terrorist activities have also increased, triggered by the recent political changes in the Middle East. Such an environment and social makeup fosters more energetic engagements in first-response robotics.

Despite having an active academic research community, experimental robotics, particularly rescue robotics, is still an underdeveloped field in Turkey. The summer school aimed to cause a rapid shift in the Turkish SSRR research and responder communities by exposing researchers and students to their international counterparts, their technologies, and the expansive collaborative approach in creative thinking and problem solving.

The summer school was held at an all-inclusive resort hotel on the Mediterranean coastline in the historical city Alanya. An on-site response robot test facility contained DHS-NIST-ASTM international test method apparatuses such as the random maze, stepfield, pipe-step, stair, ramp, and the PTZ test. Furthermore, a general-purpose workspace was made available for talks and prototyping work.

The summer school was held at an all-inclusive resort hotel on the Mediterranean coastline in the historical city Alanya.

The all-inclusive nature of the accommodation was critical. Having all facilities in one place enabled participants to focus on the work at hand, and

Figure 1. Adam Jacoff, head of the Standard Robot Test Methods development at NIST, reports on the standards effort.

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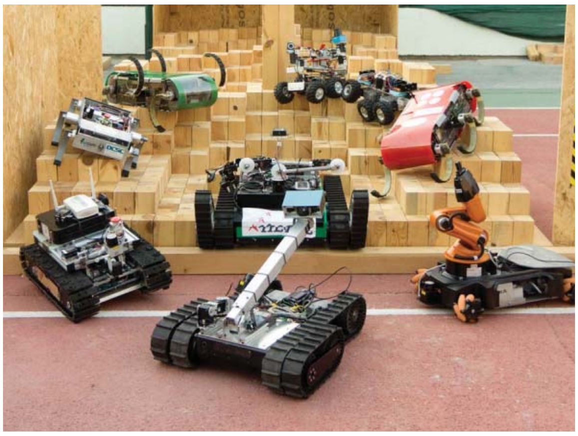

Figure 2. Robot platforms present at the event. Wheeled, tracked, and legged systems were represented.

Figure 3. Mobile manipulators present at the event.

the organized social outings allowed the participants to spend more time together, which increased the quality and quantity of the exchanges throughout the event.

Local facilities included, for the first time at such an event, resources for encouraging the participants to record and share data with real-time documentation and data logging supported by a local wiki and file share. This enabled the participants to keep notes on their creative process and store experimental data and design files collected throughout the event. The formation will be made publicly available and contributed to the appropriate existing repositories to form an ongoing archive of best-in-class implementations and information for the benefit of the wider SSRR community. Video recordings were made of all lectures as well as portions of the practical sessions. With the help of IEEE.tv these recordings will also be provided to help disseminate and promote research in this field.

The event started with a day-long tutorial on the robot operating system (ROS), a software framework that we hope will allow groups to better share their developments. The following days of the event were divided into single-track morning talks to give all the participants a broad understanding of the challenges and capabilities in this domain, and multitrack afternoon prototyping and hands-on training practicals to give the participants a deep understanding of a particular topic. On the last day, practical groups presented their work and demonstrated their implementations in the robot test facility.

In total, 20 invited talks were presented. Lectures were presented on the state and purpose of competitions and standard test methods for response robots, introducing the participants to the events and test method apparatuses used to represent requirements and evaluate capabilities. The European FP7 projects NIFTi, ICARUS, and TIRAMISU, as well as the ELROB competitions, were introduced to help the participants connect with the big European activities in this field. Talks by search-and-rescue and bomb/SWAT responders on their needs and challenges culminated in a dynamic panel discussion. Presentations about ROS, including developments in the preceding ROS RoboCup Rescue Workshop, helped to highlight its role in providing an avenue for teams and the wider SSRR community to share capabilities. This was coupled with talks on user interfaces that could run in web browsers and on classical control for robotics. Talks on different solutions to 2-D and 3-D mapping introduced the participants to the underlying theory and latest implementations. The responder representatives were particularly enthused about the possible near term applications of these technologies. Machine learning was introduced to the participants as a way to enable more complex, higher-level behaviors for mobility, manipulation, and data gathering. Finally, a talk on the broader definition and role of robot architectures helped the participants to better understand the bigger picture in the overall course of robot development.

New models were also produced for the Negotiator, Pointman, and six-wheeled HLUGV robots.

This event had six practical groups, which represented six focus areas for the SSRR community: simultaneous localization and mapping (SLAM), robot simulation in the Gazebo simulator, the robot operating system, robot design and testing, machine learning for SSRR, and user interface Design.

Despite being a teaching and dissemination exercise, we encouraged practical groups to adopt a start-up culture, trying to invent the next big thing that will change the world. We also encouraged them to find opportunities to form partnerships with other practicals in the spirit of collaborative development.

There were several salient developments made at this event. The Hector Mapping module, contributed to ROS by the Hector Darmstadt Team, was extended in several ways including a distributed implementation on low-cost "Raspberry Pi"

Figure 4. Standard DHS-ASTM-NIST robot test site on location consisting of step field, random maze, ramp, pipe-step, stair, and the PTZ test.

single-board computers and an implementation capable of simultaneously using data from multiple laser scanners. The simulation practical saw the development of software to automatically generate Gazebo models for several test method apparatuses. New models were also produced for the Negotiator, Pointman, and six-wheeled HLUGV robots. The robot design and testing practical developed several new test method apparatuses, which will now go into the standardization pipeline including new obstacles for open and confined space, a manipulation test method based on the Box Crib shoring structure that human responders use to stabilize buildings, and sensor tests that replicate the challenges of mapping confined space voids in which victims may be trapped.

The event was also highly successful in its teaching outcomes with many participants from several teams arriving with a very limited understanding of the various topics and leaving well equipped to further disseminate these technologies to their fellow team members. We saw an early example of this when one participant was able to use the materials generated during the practicals to teach another participant who had missed the bulk of the event due to a sudden illness.

The summer school saw a total of 58 participants from 16 countries representing 32 research groups, companies, institutions, and responder organizations. Significantly, we had representation from several of the main groups in SSRR research. Apart from the support of the SSRR Technical Committee, represented groups included the RoboCupRescue Robot League, ELROB, and DARPA Robotics Challenge competitions, the European projects FP7-NIFTi, FP7-TIRAMISU, and FP7-ICARUS, the Thai Robotics Society, and the Japanese response robot research community. We also had representatives from several responders representing the United States National Bomb Squad Commanders' Advisory Board, Washington State Task Force 1, and the Turkish first responders association, Arama Kurtarma Derneği (AKUT).

Preliminary signs indicate that this event has been particularly effective in sparking partnerships between these different groups, with the participants identifying areas in which they have complementary skills. It is anticipated that the coming RoboCupRescue Robot League competition in Eindhoven, The Netherlands, will see increased sharing of capabilities between teams and serve as evidence of the effectiveness of these continuing collaborations.

The demo day on Friday attracted significant domestic media interest with numerous articles in local and national newspapers, television, and online sites. This favorable coverage helps to amplify the positive effect that this event has in sparking domestic interest in this vital field among researchers, students, leaders of industry and politics, and the wider public.

This event also introduced AKUT to the use of robotics in search-and-rescue, to the standards development process and to other response organizations in an SSRR context. Being a very young, yet well-resourced, responder organization, AKUT is uniquely placed to both shape and take advantage of upcoming developments in this field. The SSRR research community looks forward to increasing collaboration with this new regional partner. Together with these domestic links, the test method apparatuses constructed for the event

Figure 5. Attendees span 16 countries and 32 groups and institutions.

will remain as a resource for local educational, industrial, and government users to help guide procurement, test products, and advance research. They also provide a seed around which a unique alternative tourism opportunity for the region can nucleate.

The SRR summer school has been effective in its goals of being a venue for the dissemination of the challenges and best-in-class capabilities in the SSRR community. It has built on the legacy of over ten years of events in this field while adding several unique features—the emphasis on responder presence, the all-inclusive nature of the venue complete with on-site test method apparatuses and IT infrastructure, and the wide variety of participants and the strong domestic interest from researchers, end users, and media. We foresee this event continuing in future years, both in Turkey and in other countries around the world, to continue pushing the boundaries of technologies that save lives.

For Further Information

For further information about this and future events, the reader is invited to visit:

http://www.ssrrsummerschool.org
http://www.robolit.com
http://www.hoteldrita.com

Acknowledgments

We would like to thank the sponsor, donors, and technical partners of this event. The IEEE Robotics and Automation Society and, in particular, the SSRR Technical Committee, provided funding for this event, including the generous student travel support grants, under the RAS Summer Schools funding program. Robolit LLC provided management for the event and donated the test method apparatuses, while the Drita Hotel donated the use of the venue and logistics. The National Institute of Standards and Technology, Arama Kurtarma Derneği, and the RoboCupRescue Robot League contributed technical expertise and experience to this event. Hokuyo Automation, through Kirinson, Inc., provided laser range sensors for the practical sessions.

We would like to thank the rest of the organizing committee: Adam Jacoff from the National Institute of Standards and Technology, Daniele Nardi from the University of Rome "La Sapienza," Gerald Steinbauer from the Technical University of Graz, Johannes Pellenz from the Bundeswehr Technical Center for Engineer and Field Equipment, and Tetsuya Kimura from the Nagaoka University of Technology.

We would also like to thank all of the speakers and practical leaders: Adam Milstein from Carnegie Mellon University, Claude Sammut, Matt McGill, and Reza Farid from the University of New South Wales, Doug Alexander and Parry Boogard from Washington State TF-1, Gabriel Lopes from TU Delft, Geert De Cubber from the Royal Military Academy Belgium, Gerhard Kraetzschmar from Bonn-Rhein-Sieg University, Jackrit Suthakorn from Mahidol University, Johannes Maurer from TU Graz, Karen Petersen and Stefan Kohlbrecher from TU Darmstadt, Kaustubh Pathak from Jacobs University Bremen, Luca Iocchi from the University of Rome "La Sapienza," Martin Hutchings from the National Bomb Squad Commanders' Advisory Board, and Shanker Keshavdas from DFKI.

Finally, we would like to thank all of the researchers and students who attended for their efforts in actively supporting the dissemination of the challenges and capabilities to help advance these life-saving technologies.

The SRR summer school has been effective in its goals of being a venue for the dissemination of the challenges

Successful Start of the RAS Technical Education Program (Formerly Summer School)

The RAS Technical Education Program (RASTEP) has successfully started, and its first supported programs have already taken place.

We are now looking for further proposals. The next deadline is 1 April 2013 for proposals for RASTEP taking place in 2014. This schedule will remain for the coming years, i.e., 1 April 2014 will be the deadline for events in 2015. The official submission of a proposal must be via email to: RAS@ieee.org

The Member Activities Board (MAB) and the Technical Activities Board (TAB) jointly run the RAS Technical Education Program. The program is intended to sponsor or cosponsor up to three programs per year around the world. One of the three programs will be fully sponsored by RAS to a level of $40,000, and it will rotate annually through RAS' three geographical regions in a round robin fashion. The other two summer schools will be cosponsored with interested organizations in the other two geographical regions up to a level of $20,000 each.

The review of proposals is based on assessments from two different viewpoints, the first one with respect to the general structure, including organizational matters and budget, and the second one with respect to the technical content:

1) The Education Committee will check the general organizational structure of the program, including budget aspects and guide through the general application process.
2) Suited Technical Committees (TCs) of the RAS have to endorse the proposal. Current TCs are listed at http://www.ieee-ras.org/technical.html

More detailed information can be found at http://www.ieee-ras.org/member.html, click on Propose an RAS Summer School.

—Andreas Birk and Paolo Fiorini

8th IEEE International Conference on Automation Science and Engineering (CASE)

By Hyouk Ryeol Choi

The IEEE CASE 2012 Best Conference Paper presented by Hyouk Ryeol Choi


Fan Tien Chen, Ren Luo, MengChu Zho, and David Orin

The 8th IEEE International Conference on Automation Science and Engineering (CASE) was held on 20–24 August 2012, in Seoul, Korea. With the theme of "Green Automation Toward a Sustainable Society," 301 papers were submitted from 32 countries all over the world and 211 papers were accepted with 171 oral presentations and 40 posters. We had two tutorials and three workshops organized. The IEEE CASE 2012 recorded the largest number of paper submission and registrations in its history. The number of participants from Asian countries such as Korea, Japan, China, and Taiwan increased compared to the previous CASE conferences and was a factor in its success. I would like to sincerely thank the contributions of all the participants as the General Chair of the IEEE CASE 2012.

The technical program consisted of 30 sessions covering health care, sustainable manufacturing, maintenance on the social infrastructures and buildings, process control, and IT-enabled systems as well as the conventional automation issues. Continuing demands for green technologies are drivers in the human-friendly and eco-friendly automation technologies, and I am very proud that CASE played a significant role in sharing them with the experts in the world.

To ensure seamless interaction among the participants, the plenary lectures were held on the opening day followed by the best conference, application, and student paper competition and the technical sessions. Plenary lectures were delivered by three top researchers in the automation field: Rainer Bischoff (KUKA, industrial robot), Tae-Eog Lee (KAIST, semiconductor manufacturing), and Kevin Lynch (Northwestern, nonprehensile manipulation).

The IEEE CASE 2012 provided the opportunity for a number of meetings, such as *IEEE T-ASE* senior editors and full editorial board, RAS AdHoc Committee on Automation, RAS Technical Activities Board, and CASE Steering Committee. Additionally, the RAS Industrial Activities Board and Standards meeting chaired by Dr. Wonpil Yu and Raj Madhavan was highlighted as a workshop with more than 30 in attendance.

A technical tour of the Hyundai, Automobile Company, Asan plant gave participants a look at the most advanced automation technology in Korea. This plant is the newest manufacturing facility among Hyundai's plants, and the nearly 30 participants had the chance to watch automation in action.

Finally, I would like to extend my great thanks to the president of RAS, David Orin, the junior president of RAS, Kasuhiro Kosuge, the vice president of the Industrial Activities Board, the chair of the Standing Committee for Standards Activities, Raj Madhavan,


Figure 1. The IEEE CASE 2012 Organizing Committee (H. R. Choi in the center in a white shirt.)


Exhibits at CASE


Peter Luh, Nak Young Chong, Chewn-Hwa, and Dong-Soo Kwon

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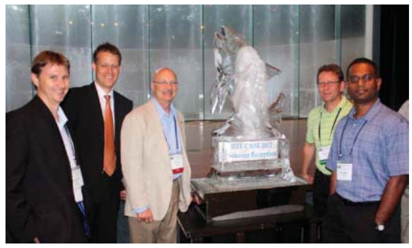
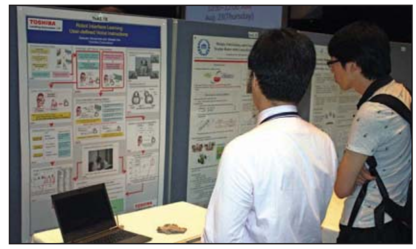
Kevin Lynch, Frank Park, and Bengt Lennartson



Jeremy Green, Rainer Bischoff, David Orin, Klas Nilsson, and Raj Madhavan



The Poster Session was very busy and well attended.

the vice president for technical activities, Satoshi Tadokoro, the president of Korea Robotics Society, Dongsoo Kwon, the robotics program director of the Ministry of Knowledge and Economy in the Korean Government, Gamchan Kang, and the other guests. They attended the conference as guests, delivered talks and encouraged us. Also, the sacrifice and hard work of the Organizing Committee and the student volunteers made the IEEE CASE 2012 possible with great success. I believe their contributions will be long remembered and am grateful for their help.

CASE Awards

During the conference, the following RAS and CASE Awards were presented:

IEEE Transactions on Automation Science and Engineering Best Paper Award

Authors: Chung-Jen Kuo (National Tsing Hua University), Chen-Fu Chien (National Tsing Hua University), and Jan-Daw Chen (Macronix International Company) for the paper "Manufacturing Intelligence to Exploit the Value of Production and Tool Data to Reduce Cycle Time."

Best Conference Paper Award

Authors: Thomas Klotz (The Fraunhofer Institute for Integrated Circuits), Norman Seßler (The Fraunhofer Institute for Integrated Circuits), Bernd Straube (The Fraunhofer Institute for Integrated Circuits), Eva Fordran (The Fraunhofer Institute for Integrated Circuits), Karsten Turek (Technische Universität Dresden), and Jens Schönherr (The Dresden University of Applied Sciences) for the paper "On the Formal Verification of Routing in Material Handling Systems."

IEEE TASE Best awardee Chen-Fu Chien (left), Editor-in-Chief Ken Goldberg (center), and CASE steering committee chair Mengchu Zhou (right)

Best Application Paper Award

Authors: Animesh Garg (University of California, Berkeley), Timmy Siauw (University of California, Berkeley), Dmitry Berenson (University of California, Berkeley), J. Adam Cunha (University of California, San Francisco), I-Chow Joe Hsu (University of California, San Francisco), Jean Pouliot (University of California, San Francisco), Dan Stoianovici (Johns Hopkins University), and Ken Goldberg (University of California, Berkeley) for the paper "Initial Experiments toward Automated Robotic Implantation of Skew-Line Needle Arrangements for HDR Brachytherapy."

Best Student Paper Award

Authors: Mohammad Reza Shoaei (Chalmers University of Technology), Lei Feng (KTH Royal Institute of Technology), and Bengt Lennartson (Chalmers University of Technology) for the paper "Abstractions for Nonblocking Supervisory Control of Extended Finite Automata."

Expanding Around the World

RAS now has nearly 120 chapters and student branch chapters in 45 countries.For the complete list, visit www.ieee-ras.org. Recently, the following Chapters have been formed:

- Benelux Section Chapter
- Ecuador Section Chapter
- Finland Section Joint Chapter
- Sri Lanka Section Chapter
- Toronto Section Instrumentation and Measurement Society and Robotics and Automation Society Joint Chapter
- Amrita Vishwa Vidyapeetham (India) Student Branch Chapter
- Institut Teknologi Bandung (Indonesia) Student Branch Chapter
- Instituto Technologico de Estudios Sup de Occidente (Mexico) Student Branch Chapter
- Instituto Tecnologico Superior de Coastzacoalcos (Mexico) Student Branch Chapter
- Netaji Subhas Institute of Technology (India) Student Branch Chapter
- Pontificia University Javeriana Sede Bogota (Colombia) Student Branch Chapter
- Universidad Nacional de Piura (Peru) Student Branch Chapter
- University of Mendoza (Argentina) Student Branch Chapter.

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RAS Elects AdCom Members

The RAS Administrative Committee (AdCom) welcomes six new members to serve a three-year term beginning in January 2013. The AdCom meets twice yearly and is charged with managing the Society as well as electing the RAS President and Vice Presidents. Congratulations to the Class of 2016.

AdCom Members Elected at Large

- William (Bill) Hamel
- Max Qing Hu Meng

AdCom Members from RAS Geographic Area 1 (the Americas)

- Ning Xi

AdCom Member from RAS Geographical Area 2 (Europe, Africa, Middle East--IEEE Region 8)

- Martin Buss
- Jianwei Zhang

AdCom Member from RAS Geogrpahical Area 3 (Asia, Australia, Pacific Rim)

- Kazuhito Yokoi

RAS Technical Committees

Aerial Robotics and Unmanned Aerial Vehicles
Agricultural Robotics
Algorithms for Planning and Control of Robot Motion
Automation in Logistics
Autonomous Ground Vehicles and Intelligent Transportation Systems
Bio Robotics
Computer and Robot Vision
Energy, Environment, and Safety Issues in Robotics and Automation
Haptics
Human-Robot Interaction and Coordination
Humanoid Robotics
Marine Robotics
Micro/Nano Robotics and Automation
Mobile Manipulation
Networked Robots
Performance Evaluation and Benchmarking of Robotic and Automation Systems
Rehabilitation and Assistive Robotics
Roboethics
Robot Learning
Safety Security and Rescue Robotics
Semiconductor Manufacturing Automation
Service Robotics
Smart Buildings
Software Engineering for Robotics and Automation
Space Robotics
Surgical Robotics
Sustainable Production Automation
Telerobotics

For complete details, visit www.ieee-ras.org.

Technical Committee

The RAS Technical Activities Board (TAB) focuses on the research content of RAS, tracking technical developments and encouraging innovation in applications, theory, models, metrics, experiments, architectures, products, initiatives, and other technical areas. TAB also oversees the 28 technical committees (TCs) covering a range of areas within robotics and automation.

As the field continuously changes, the establishment of new TCs is important. If you would like to recommend a new TC, please refer to www.ieee-ras.org and send a proposal to Satoshi Tadokoro, vice president of Technical Activities at tadokoro@rm.is.tohoku.ac.jp.

Call for Award Nominations

The nomination period is open for the IEEE Fellow Class of 2014 and will continue up to 1 March 2013. Nominees must be IEEE Senior Members or IEEE Life Senior Members with contributions in advanced engineering, science, and technology, bringing significant value to society. Members can be nominated in one of four categories: Application Engineer/Practitioner, Educator, Research Engineer/Scientist, or Technical Leader. For more information and detailed instructions for preparing the application, please visit the IEEE Fellow Web site at www.ieee.org/fellows.

The IEEE/IFR Invention and Entrepreneurship Award recognizes the entrepreneurial commercialization of ideas into actual products. Nominations are due by 1 March 2013 and require citations and description of the original work that has been translated into commercial application as well as the commercial product and its success. The nomination must also describe the unique characteristics of the transformation into the commercialized product that justify the award. The current and future impact of the commercial product is a fundamental element of the merit for selection. The US$2,000 prize is cosponsored by the IEEE and International Federation of Robotics (IFR), and the award is presented during the IERA workshop. For complete details and the application form, visit www.ieee-ras.org.

The Robots Are Coming … to the iPad

The IEEE recently launched Robots, an iPad app featuring some of the world's most advanced robots. The app includes 126 robots from 19 countries—many of the robots created by the RAS members! Users can play with interactive animations and 360° images of robots, read detailed technical specs about each robot, and view hundreds of photos and videos.

This app was created by the editors of *IEEE Spectrum*. The goal is to bring the world of the robotics to a broad audience, from young people who are interested in the field to the researchers who want to learn more about robot projects around the world.

To prepare the app, the *IEEE Spectrum* robotics editor Erico Guizzo and photo editor Randi Silberman Klett contacted hundreds of researchers and robotics companies to collect data and images. The result is a richly interactive app that includes 34 interactive animations, 589 photos, 42 audio interviews with roboticists, 446 selected videos from YouTube, plus articles, a glossary, and a timeline of robotics and artificial intelligence.

The Robots app is available in Apple's App Store. To learn more, visit http://robotsapp.spectrum.ieee.org

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John McCarthy

By Selma Šabanović, Staša Milojević, and Jasleen Kaur

John McCarthy is best known as one of the founding fathers of artificial intelligence (AI), a term he coined in 1955, and much has been written about his pioneering work in computer and cognitive science (Figure 1). Less attention has been given to McCarthy's efforts related to robotics, though his AI research instigated and influenced development in the field. As the founder of the Stanford-AI Lab (SAIL) and its director from 1965 to 1980, McCarthy participated in research on computer vision, speech recognition, and planning in robotics, collaborated with innovators such as Bernie Roth and Vic Scheinman to develop some of the first robot arms, and advised 30 students, a number of whom have gone on to become leaders in robotics and AI.

Under the aegis of the IEEE Robotics and Automation Society (RAS), we had the opportunity to interview John McCarthy and some of his students and colleagues, including Bernie Roth, Vic Scheinman, and Ruzena Bajcsy. This article draws on their narratives and experiences, particularly looking back at McCarthy's early work in AI and robotics. Unless stated otherwise, direct quotes are excerpted from our interviews.

The Idea of Intelligent Machines

Born in Boston in 1927, John McCarthy was a child prodigy [7] and spent his education and career surrounded by other talented and forward-thinking individuals. He graduated from the prestigious Belmont High School in Los Angeles two years early in 1943. He went on to receive his B.S. degree in mathematics from Caltech in 1948 and his Ph.D. degree in mathematics from Princeton University in 1951.

McCarthy's lifelong interest in AI was sparked by the Hixon Symposium on Cerebral Mechanisms and Behavior he attended at Caltech in 1948. The well-known version of the story states that McCarthy first heard about the notion of machine intelligence in a paper presented at the symposium, which was also attended by John von Neumann, Warren McCullough, Alan Turing, and Claude Shannon. In our 2011 interview, McCarthy explained that he himself had recounted this story for years, but later learned that it was incorrect: "When I got the Kyoto Prize [in 1988] and was asked that my lecture be autobiographical, I went back to look up who had talked about using computers to behave intelligently [at the Hixon Symposium], and discovered that no one had. That I had simply jumped to the conclusion that people were interested in that." This propitious assumption put McCarthy on a pioneering research trajectory in the field of AI.

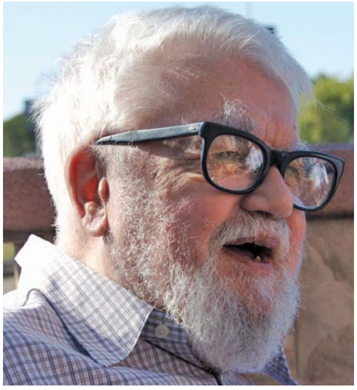

Figure 1. John McCarthy in 2006. (Photo courtesy of http://www.flickr.com/photos/null0/272015955/.)

Working Towards AI

McCarthy decided that the way to develop an intelligent machine would be to put it through a process of evolution similar to that undergone by a human brain, which needs to interact with its environment to become smart. His initial proposal was an experiment with two interacting finite automata, in which one automaton acted as a "primordial bit of life" and the other as its environment [8]. When McCarthy had a chance to discuss his idea with von Neumann at Princeton in 1948, von Neumann enthusiastically told him to "write it up, write it up!" [1]. With a self-censorship that seems characteristic of his early years, McCarthy decided that his ideas of "a probabilistic model of automaton connected to a brain... were not very good," and did not put his thoughts to paper until 1959. The article he published then, "Programs with Common Sense," suggested that a computer that could evolve human-level intelligence would need to have formal representations of people's common-sense knowledge in the course of their everyday activities. This was a seminal paper for logical AI and marked "the birth of the field of knowledge representation" [7].

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After getting his doctoral degree in 1951, McCarthy spent two more years at Princeton as an instructor, where he met his longtime collaborator, Marvin Minsky (see Figure 2). After Princeton, McCarthy accepted an assistant professorship of mathematics with Stanford University and worked there until being let go in 1955. McCarthy describes himself during that period as being "distracted by thinking about AI" rather than pure mathematics and working on ideas that would need years of development before they were publication-worthy. McCarthy's next position was at Dartmouth College, where he and Minsky, along with Claude Shannon from Bell Labs and Nathaniel Rochester from IBM, held "The Dartmouth Summer Research Project on Artificial Intelligence" funded by the Rockefeller Foundation. This watershed event not only introduced the now ubiquitous term "artificial intelligence" into the public lexicon but also allowed four pioneering researchers—McCarthy, Minsky, Newell and Simon—to develop plans for creating a new discipline of AI.

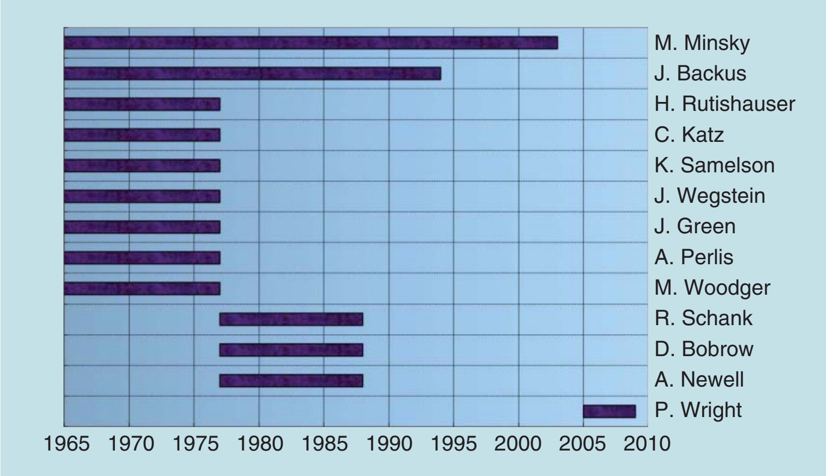

Figure 2. John McCarthy's collaborator timeline created using bibliographic information.

A Maturing Career

Minsky and McCarthy met again at the Massachusetts Institute of Technology (MIT), where McCarthy went on a Sloan Fellowship in 1956 and stayed as a professor until 1962. The two colleagues founded the MIT AI Lab, which made significant achievements in a variety of fields, including robotics, the theory of computation and common-sense reasoning, and human–computer interfaces. The lab was founded using resources obtained in a chance corridor encounter between McCarthy, Minsky, and Jerome Wiesner (see "McCarthy on Founding the MIT AI Lab"); McCarthy explains that this type of "lucky" access to resources happened throughout his career and allowed him not "to become anything like an expert on funding" until much later [5].

While at MIT, McCarthy also started research on a number of topics that would occupy him throughout his career, including timesharing, automated theorem proving, and machines that can develop common sense. He also created LISP, the second longest used programming language today (FORTRAN is the longest) [7] (see Figure 3). Despite his productivity, McCarthy was still not fully confident of his approach in these early days, and avoided peers and senior colleagues he suspected might not like or accept his ideas: "Unlike Minsky, who has a big talent for knowing everybody, I don't have that talent, and when I was at MIT, I never went to see [Warren] McCulloch, although I should have. And actually, I attempted to avoid Norbert Wiener because, having read his book, I didn't think he would like my ideas" [1]. In hindsight, McCarthy regretted these missed opportunities to communicate with colleagues.

By 1962, McCarthy's reputation had grown, and he had been promoted to an associate professor at MIT. Then, Stanford University, which had let him go seven years earlier, approached him to join their faculty. This started a bidding war between Stanford and MIT (see "John McCarthy on MIT and Stanford Bidding War"). McCarthy eventually decided to go back to Stanford University as a full professor with the Division of Computer Science, which would become the Department of Computer Science in 1965. He spent the rest of his career there, retiring in 2001.

McCarthy on Founding the MIT AI Lab

"Now, here's my version, which may not be entirely correct. I encountered Minsky in the corridor and said, 'We really ought to have an artificial intelligence laboratory.' And he said, 'That's a good idea. Let's do that.' And then along came Jerry Wiesner, who was the head of the Research Laboratory of Electronics. And I said, 'Marvin and I want to have an artificial intelligence laboratory.' And he said, 'All right. What do you need?' And I said, 'We need a room, and a secretary, and a keypunch, and two programmers.' And Wiesner said, 'And how about six graduate students?' And we said, 'Yes.' And that was it. And the reason why was that MIT had just received a Joint Services contract, and MIT had divided the prize up among various departments, and the Mathematics Department's share was support for six graduate students. But it wasn't clear what this Joint Services contract would do with the six graduate students. So when Minsky [and I] came along, Wiesner had a solution to his problem and sent over his six graduate students, so somehow the resources were suddenly available. It spoiled me in the sense that I felt that that's the model of a proposal and its acceptance. You meet the guy in the corridor and ask him, and he says, 'Yes.' He says, 'What else do you need?'"

From AI to Robotics

While at SAIL, McCarthy became interested in robotics as a demonstration and test of his theories regarding AI. He supervised robotics-related research on computer vision, speech recognition, and manipulation, and later worked with the Stanford cart. McCarthy's doctoral student Raj Reddy recounts that, in the 1960s, research in the lab focused on the idea that "if you could study speech, vision, robotics, languages, then the sum totality of understanding those things would lead us to understanding the nature of intelligence" [10]. Robotics at SAIL was funded initially by a grant that McCarthy received from the Advanced Research Projects Agency (ARPA) of the Department of Defense in 1965 (Contract SD-183). McCarthy applied for the grant so that he could purchase a PDP-6 computer, which had a large memory that would enable him to do more advanced work on logic-based AI: "I would need a big memory for a big LISP system." Robotics was included to make the grant more attractive to ARPA.

Through robotics, McCarthy particularly wanted to support his notion of "description, not discrimination," which ran counter to "the 1950s notion of pattern recognition, namely, regarding a pattern as being defined as some Boolean combination of elementary characteristics" [5]. He was interested in machines that could not only discriminate objects but also act in the world: "You can make enough combinations to

While at SAIL, McCarthy became interested in robotics as a demonstration and test of his theories regarding AI.

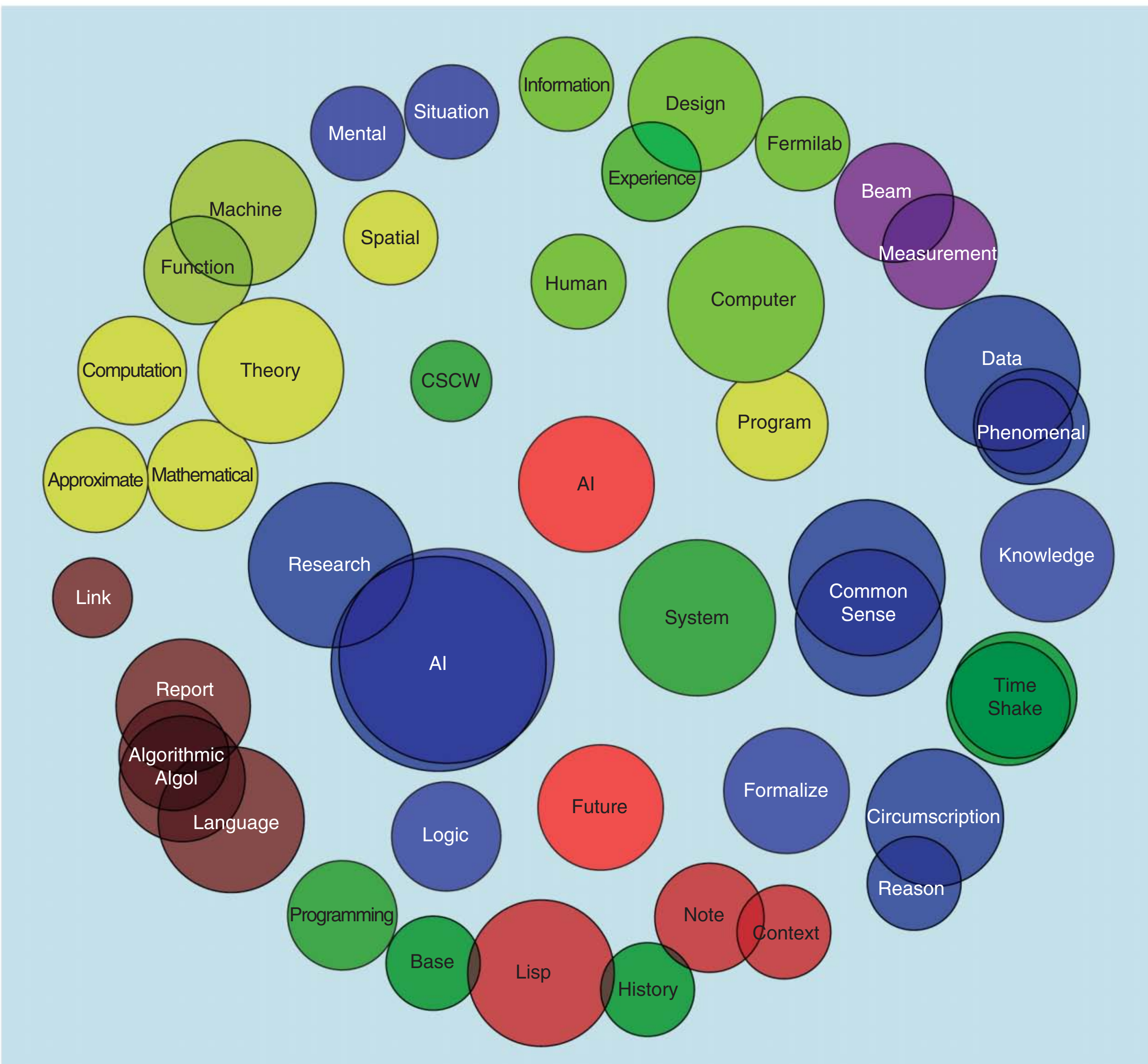

Figure 3. The 50 most commonly used words in the titles of John McCarthy's publications, clustered using multidimensional scaling, show the main themes in his research.

John McCarthy on MIT and Stanford Bidding War

"By the spring of '62, I had been promoted to associate professor at MIT and I got, quite out of the blue, a telephone call from George Forsythe at Stanford, who asked me if I'd be willing to come to Stanford. Being slightly miffed by Stanford having previously decided not to keep me, I said, 'Well, I've been at Stanford before. I could only come as a full professor.' And I thought that would turn him off, but he said, 'I think I can manage that.' And I was very startled, because I'd been just made an associate professor at MIT, and that would be a jump in one year to full professor. [Forsythe] had the ambition to have a computer science department, and I already had developed some reputation there. connected with AI, and also with proving facts about computer programs.

There was also a jump in salary associated with the Stanford offer. Now, MIT was willing to more than match the salary, which was startling to me. From US$9,000, MIT was willing to go to US$15,000, but they weren't willing to make me a full professor right away, because they considered Minsky and me to be a pair, and... didn't feel they could promote one without the other. We were in different departments, and the Math Department would have had to agree to promote Minsky. They were willing to make me the director of research for the Computer Science Department, and so forth. But I really did like California and wanted to go back, so I ended up accepting the Stanford offer. I hate shoveling snow out of my driveway."

Bernie Roth on Meeting McCarthy and the Rancho Arm

"That's another one of these life things, which are accidents that change your whole life. I was a young professor. I'd been here, say, two years, if that long. I was minding my own business, and I got a phone call. And at the other end was this august figure, Fredrick Terman, who was provost and had sort of an autocratic reputation. And it turns out that John McCarthy, who was the professor of computer science, also a young professor, had gotten a big grant, like a million dollars, which was a lot of money in those days, to start what was called the Stanford Artificial Intelligence Laboratory. And part of the thing was that they were going to build robots. And somehow, Terman, who kind of had his ear to all the vibrations, got some word from someone that John was a great mathematician but maybe not the right guy to build mechanical things and that he ought to provide some backup or something like that. So, he called me and he suggested I get in touch with John McCarthy. And I think he called John and suggested he get in touch with me. And so we got in touch with each other, and the rest is history.

So, you know, we met and I sort of took on the part of the projects that would involve building mechanical arms, which is what we called robots in those days. So I started to essentially supply mechanical arms that they could whiz around with the computers. And they had the illusion, the computer guys, that they could do anything. And, you know, you didn't have to worry about the mechanical things. They just could do anything at any speeds, and they had all these exaggerated notions of catching flies in the air and stuff like that. [laughs]. And they were very anxious to get started.

So the first thing I did is, I knew of a prosthetic arm. It's sort of like an arm brace, essentially, but it had electric motors. It was for people that were paralyzed, and it had a tongue switch. So with your tongue, you could control the motors, and you could get your arm to move. It turns out it was very, very flimsy because it relied on the structure of the human arm to give it, you know, strength and stability. So without an arm in it, if you moved it, it would vibrate, you know. So after a while, we would get the people who called it 'Shaky.' And then when we put a mechanical hand on it, it would drop stuff, so they called it 'Butter Fingers.' It had various different names at the time. But basically, that got us into the business very quickly of being able to have a computer control an arm. And that was the objective, to just get going as quickly as we could."

discriminate the alphabet, but my complaint is it wouldn't enable you to draw a letter. And in particular, I pointed out that if you wanted to do manipulation, then description was what you needed of the objects that you were going to manipulate" [1]. This research eventually led to the first hand–eye computer system, which was developed by McCarthy and Lester Earnest; it allowed a computer to recognize real blocks using a video camera and then control a robotic arm to stack or arrange them in the physical environment. McCarthy also found that robots were useful for presenting the capabilities of AI to the public. When Walter Cronkite came to interview him, McCarthy "did not try to make him understand this more abstract notion of discrimination versus description" but showed him robots instead.

Stanford's First Robots

McCarthy's desire to develop AI through robotics research spurred the construction of numerous robotic platforms, particularly a series of mechanical arms using the resources ARPA put at his disposal. McCarthy, however, was not an engineer, so provost Frederick Terman called in Bernie Roth, a mechanical engineer who had recently become an assistant professor at Stanford University, to build robots for SAIL. Victor Scheinman, a graduate student whom McCarthy describes as "a real genius as a mechanical engineer and designer" [1], worked with Roth to develop arms that the members of SAIL could use for their research.

The first robot arm they developed was the Rancho Arm, a prosthetic arm that Roth purchased from the Rancho Los Amigos hospital in Downey, California, and modified so that it could be used with computers (see "Bernie Roth on Meeting McCarthy and the Rancho Arm"). The arm, however, was flimsy, inaccurate, and very difficult to control with a computer. The next arm the team built was digital and designed to be more suitable to computer control. Vic Scheinman describes it as "essentially. a pneumatic arm. It had a bunch of plates, and these plates were controlled by. inflatable actuators, which could either be inflated—call it a one—or deflated—a zero. And there were four actuators between each set of plates. So imagine a stack of plates, with four actuators between it. And so imagine 4-b word positions, although there was some amount of overlap there. But you could have a 4-b word

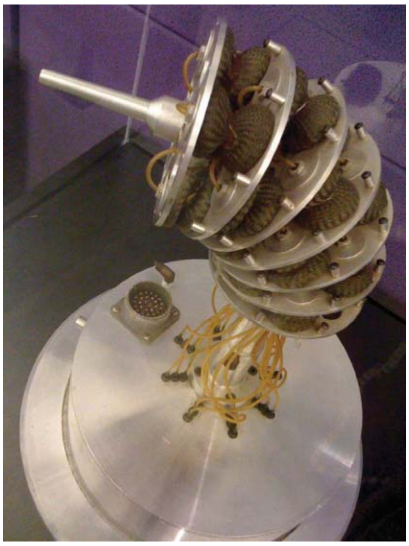

Figure 4. The ORM on display in the Computer History Museum in Mountain View, California. (Photo courtesy of Selma Šabanović.)

Vic Scheinman on the Stanford Arm

"I was asked to design an arm that really could be used by the computer, and I designed an electric arm. And essentially, I was given sort of carte blanche to do something, and this arm here, the Stanford Arm was the product. And I did that as my engineer's degree thesis, just the design of the arm. I didn't build it at the time, or I started to build parts of it. I tried to incorporate various other features, which were interesting to me. It's a six-degree of freedom arm, with a one-degree of freedom proportional hand, so it's a seven-degree of freedom robot, all electric. And it had brakes on the joints, such that we could run it in space war mode, but then you could turn it off and then the arm would sort of sit in a static position until you've finished your computations for the next move, and then it would go on. Whereas the hydraulic arm, if you turned off the computer, it would collapse. This one didn't. And it became a sort of a workhorse. I left Stanford at that time, after my engineer's degree, in 1969 I think it was."

theoretically defining the positions of each plate." As the arm looked "very snake-like," according to Roth, it was named the ORM—the Norwegian word for snake (see Figure 4). The team soon found out that this design also had problems, particularly difficulties with control because of indeterminacy caused by the actuators inflating and deflating, but through it they worked on the idea of digital control.

The third arm was built using hydraulics, with speed as the main design goal aimed at taking advantage of the increased speed of computers. McCarthy recalls Vic Scheinman working on "these plastics tubes that had high pressure hydraulic fluid in them. I didn't do any close supervision of that, but if one of those tubes ever broke, that arm would swing and anybody who was in the way would really get hurt. So it was put into a little house that was built around it, but it was never used" [1]. Roth also commented on the arm's power: "It was scary, because it was this really powerful thing, and there was always a lot of concern about people getting hurt. So we built a room around this arm. I made sure the students bought shatter-proof glass to put in, especially near the controller. Some years later, I found out that they had dropped a piece of the shatter-proof glass on the way in and they didn't want to tell me, so they replaced the one right in front of the controller with ordinary glass. But nothing had happened, so that was okay" [3]. This arm was also not very well suited to the computer environment—it was difficult to run using a timeshared machine because it needed real-time control and had to run in what Scheinman referred to as "space war mode," and "it had hydraulic oil, it had leaks, and the floor got sticky" [4]. By 1969, Scheinman had built a fourth smaller and weaker electrically powered arm, which became the "workhorse" in SAIL (see Figure 5 and "Vic Scheinman on the Stanford Arm").

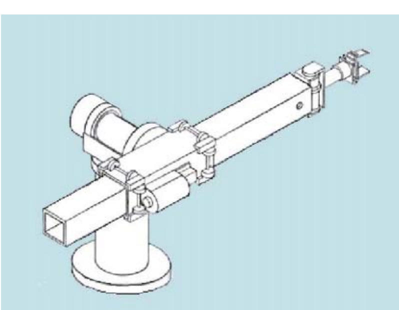

Figure 5. Sketch of the Stanford Arm from Victor Scheinman's thesis (1969).

Designing manipulators allowed the engineering faculty and graduate students at Stanford University to develop a science and theory of mechanical design, particularly in the kinematics of arms. For a while, it seemed the computer science research was lagging behind the developments in robotics. Bernie Roth remembers John McCarthy quipping at him during a meeting, "You know, we've turned out a few really good theses in mechanical engineering. Why don't we turn out something in computer science?" [3]. With more capable robots available, McCarthy and his students were soon able to turn their focus to innovations in computer vision, speech recognition, and planning.

Computers with Hands, Eyes, and Ears

McCarthy's early expectations for the possibilities of working with robots were very optimistic. In the beginning, he imagined that they "would be assembling a Heathkit [consumer electronics equipment sold in the form of a kit to be assembled by the purchaser] in a couple of years. The Heathkit involved point-to-point wiring and soldering, which of course is something that nobody has even done today" [1]. Although the challenges of this project became clear quite quickly, the notion of using computer vision, AI, and robotics together would be a continuing theme of work in SAIL.

The SAIL team, led by McCarthy and with the assistance of Lester Earnest, developed the first hand–eye computer system using a camera and robotic arm to move blocks and do assembly tasks. They also worked with a robotic vehicle—the Stanford cart—guided by visual information from a video camera. However, the two were never integrated to produce a mobile robot with a manipulator. McCarthy explains, "We could, in principle, have

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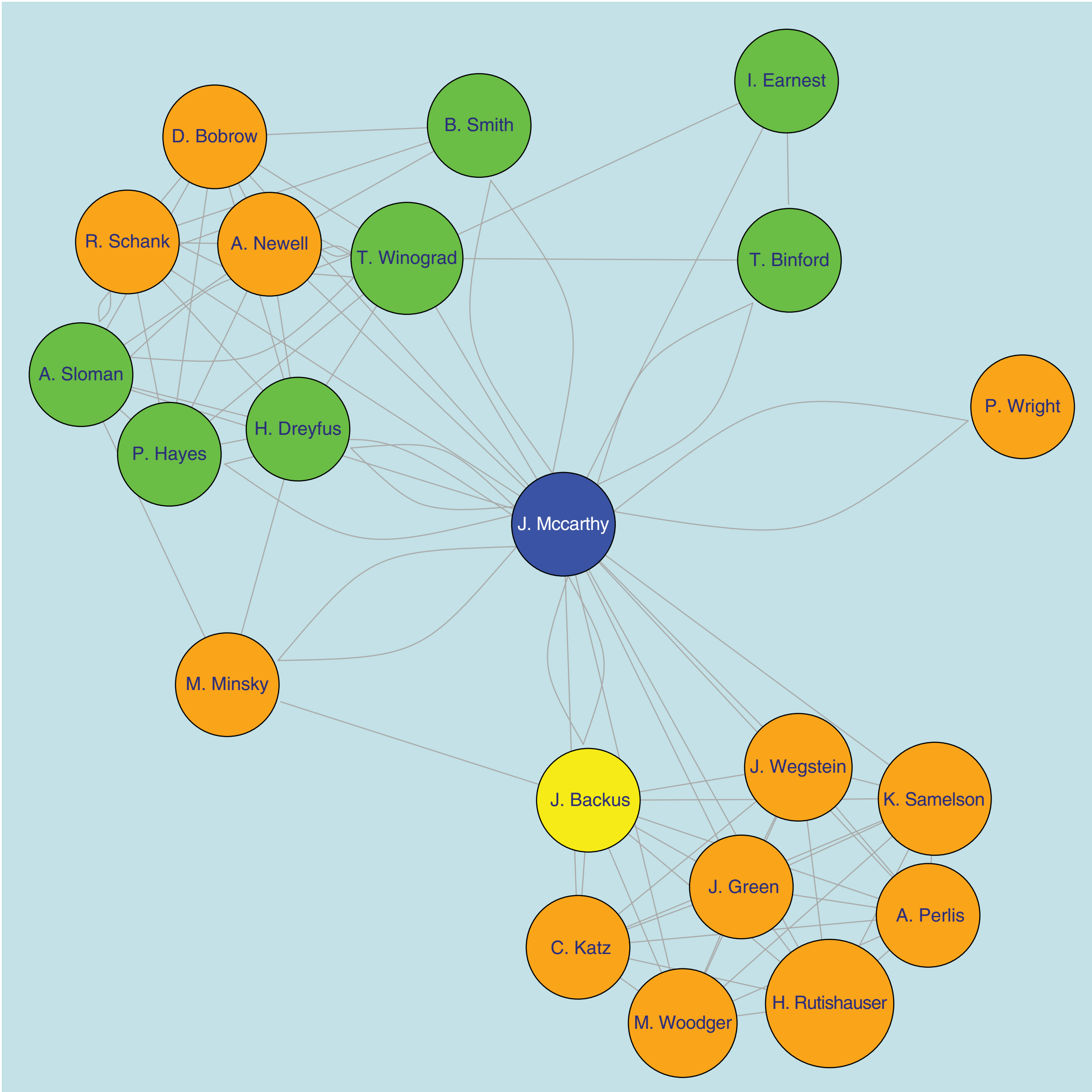

Figure 6. John McCarthy's coauthorship network showing 21 collaborators who authored three or more papers with him. Green is used for authors who wrote three papers with him, orange is used for authors who wrote four papers with him, and yellow is used for authors who wrote five papers with him.

put the arm on the cart, and so forth, but remember that all of these things were done on a PDP-6 computer in a timesharing mode on—well, it was possible to sign up for time for wee hours of the morning,… there was a complicated sign-up. I don't think I remember that because I never bothered with it because my own use of the computer was not CPU intensive. I never did use it for anything but a typewriter, for writing papers" [1].

The AI lab members developed a range of innovations around the notion of "computers with hands, eyes, and ears" (or "cameras, microphones, and manipulators") in SAIL's first ten years: programs for point to point control of arm movements, computer servoing, a laser ranging apparatus, programs for the symbolic description of complex objects and a simple system that located blocks visually and sorted them into stacks, an obstacle-avoidance program for the arm working in crowded environments, and planning for robotic arms. For the most part, the researchers worked on these projects separately. Raj Reddy recalls that, in fact, the only time that the research in speech, vision, and robotics really came together was in "a paper in the Fall Joint Computer Conference in 1968, called 'A Computer with Hands, Eyes, and Ears,' where we tried to integrate the speech research

IEEE ROBOTICS & AUTOMATION MAGAZINE

CALL FOR PAPERS

Special Issue on Stochastic Geometry in Autonomous Robotics

Guest Editors: Martin Adams, Ba-Ngu Vo, and Ronald P. Mahler

Deadline for paper submission: 10 January 2013

Introduction: The robust interpretation of an autonomous vehicle's environment, as well as its own position in that environment, underlies almost all autonomous robotic applications. This Simultaneous Localization And Map building (SLAM) problem requires a robust representation of the vehicle's surroundings (the map) in the presence of sensing/feature detection uncertainties such as false positives, missed detections and spatial errors. Significant research activity now exists in representing both measurements and the feature based SLAM map as a Random Finite Set (RFS), rather than the conventionally used random vector. This is not merely a triviality of representation. Recent research has shown that Finite Set Statistics (FISST), developed for data fusion and estimation with RFSs, when applied to sensor representations and SLAM, can eliminate the necessity of fragile map management and feature association algorithms. Implementations in the form of the Probability Hypothesis Density (PHD), Cardinalized PHD (C-PHD) and Multi-Target, Multi-Bernoulli (MeMBer) filters have already demonstrated robust means of representing uncertain sensor data and maps, with the unique abilities of jointly tracking both object spatial and existence uncertainties. The RFS map concept therefore provides a robust paradigm under which the true number of features, which have entered the field(s) of view of an autonomous vehicle's sensor(s), as well as their locations, can be jointly estimated in a Bayes optimal manner, while taking into account feature detection and false alarm probabilities.

Scope, Description and More Information: This special issue calls for magazine style articles on the direct application of FISST to the issues of autonomous robotic sensing, mapping and navigation with diverse sensing techniques and in various environments. The robustness of the solutions presented should be demonstrated in the presence of sensing and sensor processing uncertainty. Comparisons with conventional vector based techniques are also encouraged. Topics of interest include, but are not limited to,

- Use of Sets for Sensor and Map Representations,
- PHD Smoothing and Filtering Applications in Robotics,
- Sensing, Mapping and SLAM in high clutter levels,
- Multi-Vehicle SLAM,
- Jointly incorporating object existence and spatial uncertainties into mapping and SLAM
- Metrics to determine full mapping and SLAM errors
- Detecting and Tracking Extended Targets

Complete details at http://www.ieee-ras.org/ram/specialissues.html

Digital Object Identifier 10.1109/MRA.2012.2221280

and the vision research and the robotics work into a single system. We tried to say 'Pick up the red block on the bottom corner,' and the vision system would look at it and decide which one it was and just pick it up and stack it, or do something. And that's the first time we discovered the complexities of systems integration, taking all this different software written by different people and putting it into a single working unit. And what we thought would take one month took about a year" [10].

The work on hand–eye problems led to more practical applications for industry, such as the automation of the assembly of a water pump using visual, tactile, and force feedback; this work was later extended in the development of further "programs for manipulation and assembly of objects from parts" [6]. As well as being a natural application of their research on vision and robotics, industrial applications allowed McCarthy to further consider the differences between human and machine intelligence: "I once paid a visit to IBM, where they were doing some automatic assembly—partial automatic assembly. It was very interesting there because you could see things being assembled automatically, and then there was some part of the work where it would suddenly expand out to a part where it couldn't be done automatically. And you had a department of 40 women doing a manual assembly of some part of it." Rather than replicating human intelligence, McCarthy's experiences with robotics and AI led him to consider that the immediate promise in machine intelligence was not in their likeness to humans but in areas where it would be useful to use their ability to "see things and hear sounds that a person cannot, and they may be faster, stronger, more economical, or more expendable" [9].

Another lasting legacy of McCarthy's work is his students.

His work on robotics also inspired McCarthy to work on the frame problem—how to mathematically describe the effects of a system's actions succinctly, without having to describe its multifarious and mundane noneffects—and become one of the first people to deal with it in the context of robotics through circumscription and nonmonotonic reasoning. This was another way in which developments in logical AI and robotics went hand in hand.

A Continuing Legacy

John McCarthy's intellectual legacy as a visionary and founder of the field of AI includes developing one new programming language (LISP) and significantly influencing the development of another (ALGOL), popularizing the idea of timesharing, and relentlessly following his passion of creating intelligent machines. Along the road, he collaborated with some of the biggest names in their respective areas (see Figure 6), including fellow mathematicians (Marvin Minsky, Allen Newell), computer scientists (John Backus, Terry Flores, Pat Hayes), and philosophers (Hubert Dreyfus).

Another lasting legacy of McCarthy's work is his students. Over the course of his career, McCarthy advised 30 students. Some of them—including Ruzena Bajcsy, Raj Reddy, Hans Moravec (coadvised with Tom Binford), and Rodney Brooks—went on to have very successful research careers in robotics, and others have contributed to computer science and AI. His students knew him as an understanding and supportive mentor. Ruzena Bajcsy spoke of him "as a good friend. I really cherish our relationship. I have lot of affection for him. He really facilitated, enabled who I am, absolutely. And I will be indebted for that forever" [2]. She still remembers his assistance during her first years in the United States while she was getting used to working in a new discipline and educational system after coming from Czechoslovakia: "My first exam was a failure, but Prof. McCarthy was very kind to me and he supported me, and so I got a second chance, which I passed." Raj Reddy, whose own pioneering research in speech recognition was supported by McCarthy's ARPA funds, sees him as an enabler, "basically [John] was able to kind of collect and let people do their thing" [10].

Although McCarthy certainly did not lack ideas or the passion and talent to develop them, early on in his career, he at times lacked confidence that the authorities would agree with him. This led him to strike his own course, and perhaps to emphasize the novel perspectives young researchers can bring to science. When we asked him what advice he would give to young researchers interested in pursuing careers in AI and robotics, he said: "If they're as self-confident as I was, then I would recommend to them don't pay any attention to anybody's advice. Think about it for yourself. I think AI needs new ideas and it's most likely to come from new people" [1]. His own example speaks volumes to the effect a fresh perspective can have.

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WIE-RAS Mentors Inspire the Next Generation of Women Engineers

By Xiaorui Zhu

One of the primary goals for the Women in Engineering (WIE) of the IEEE Robotics and Automation Society (RAS) is to promote female involvement in robotics and automation in our worldwide community.

In an effort to do so, we try to encourage young girls who want to get involved in engineering. Proudly speaking, some senior members of our committee are doing just that. As commendable volunteers and mentors, these women were inspired and encouraged by someone when they were young, so they give back to the next generation of young girls in their neighboring communities.

I am pleased to announce that we are launching a series of articles from WIE-RAS members in this column. These women are all involved as mentors in the For Inspiration and Recognition of Science and Technology (FIRST) Robotics Competition. Not only are the WIE-RAS members highly respected in the field but also in their communities. I am happy to share this space, so that their stories can be told.

Monica Visinsky

Senior Engineer Oceaneering Space Systems, Houston, Texas

When I was young, my parents were always encouraging and supportive of my interests. It just seemed to be a given that I would go to college. I had the lofty goal of becoming an astronaut and therefore, to go into the space industry, chose engineering as my major. I trained as a computer/electrical engineer with a robotics focus in graduate school. While I have yet to be selected as an astronaut, I have worked for Oceaneering Space Systems and supported NASA's Johnson Space Center (JSC) with the International Space Station Dexterous Robotic System for just over 16 years.

When Oceaneering asked for volunteers to help mentor a fledgling FIRST Robotics team for Friendswood High School 15 years ago, I thought it sounded like a fun chance to share my enthusiasm for robotics. Friendswood opted to dissolve their FIRST team after three years due to the expense, so I went to help out the NASA JSC-sponsored Clear Creek Independent School District (ISD) FIRST Team 118 (Robonauts). A year later, the Pasadena ISD Team was asking for a sponsor, as their previous sponsor had backed out. Oceaneering offered to fill that void, and I have been mentoring the Pasadena FIRST Team 231 (High Voltage) ever since.

Pasadena, Texas, is a more industrial town, with many companies supporting the petroleum industries and other local refineries. It was surprising to me how many of the students on our team, which draws from five local high schools, do not expect to go to college. It has been a joy to watch their eyes open to the possibility of going on to continue their education and to the potential to work in engineering. There are always young women on our team, and they are often the most enthusiastic to learn new skills. They are freed by the camaraderie of the team and the common goal to build a full-scale, functioning robot in only six weeks and to be able to learn how to use even the more complex tools like the mill or the lathe. Several years in a row we were even able to get a summer internship for these enthusiastic young women at NASA's JSC. I am honored to be able to show them the many different aspects of engineering and that it can be fun and lead to a rewarding career.

High Voltage, FIRST Team 231, is a veteran team with many accomplishments (Figure 1). We did especially

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Figure 1. Team 231 at the FIRST 2012 Alamo Regional.

well this past year—winning the Alamo Regional and gaining the silver medal in the Nationals Galileo division. While the winning is a real boost for the morale of our students, these events also allow the kids to interact with thousands of other students from around the world who are enthusiastic about math and science. One of the goals of FIRST is to promote gracious professionalism. I am greatly encouraged to know that our students often go out to help other, newer teams who may be having software issues or need help in finishing the building of their robot so they can compete. It can really broaden the horizons for students who may never have traveled outside of Texas. Our team has formed a special bond with Team 3103—an all-girls school from Houston—as we see them at many of the same events. They, and the other all-girls teams in FIRST, help show not only our young women but also the young men that women can achieve anything.

Monica Mohtasham

Senior Project Engineer
Pratt & Whitney, East Hartford, Connecticut.

I started my technical career during and after high school. I went to a vocational-technical high school in Manchester, Connecticut, and chose the field of electronics to study for four years. After high school, I joined the U.S. Navy and was a radar technician for P-3 aircraft located in Oahu, Hawaii. I took more than a few years off before going back to college after the service, and I received my bachelor's degree in electrical engineering from the University of Connecticut in 2004. I have worked at companies such as Connecticut Light and Power on the local electrical distribution grid and UTC Power on electrical systems for proton exchange membrane, polymer electrolyte membrane and phosphoric

Figure 2. Team 3182 third-year anniversary collector pin.

acid fuel cell test stands. In 2012, I received a master's degree in systems engineering from Worcester Polytechnic Institute; I am able to utilize the skills I obtained to lead projects and to deal with customer requirements and project development from beginning to end. I have been with Pratt & Whitney for almost two years in the Military Engines Division in the Support Equipment Operations Group. I work in the Engine Test Systems and Services Department as a project engineer supporting test cell installation and modifications at customer sites all over the world.

I mentored an all-girls FIRST robotics team, named Athena's Warriors (Team 3182), located in West Hartford, Connecticut (see Figures 2–7), that is partially sponsored by United Technologies and promotes girls in the science, technology, engineering, and math (STEM) fields in the greater Hartford area. Figure 3 is a team photo during the 2012 FIRST free competition. This team will be entering its fourth year of competition. It has definitely been a rewarding experience that can support girls on this team through a journey of discovery and awareness of what STEM fields involve and how they can be a part of it. The FIRST organization started by Dean Kaman in 1992 is based on one concept—bringing STEM fields closer to the next generation, our children and their children, to not only enrich their lives and livelihood but also to bring our nation back to the forefront of engineering and science. FIRST just celebrated its 20th year and is growing every year.

Over the last couple of years, I have been asked whether having an all-girls team is the right thing to have, especially in light of the fact that when the girls leave this venue, they will most likely enter into a world where there are no other girls to work with,

Figure 3. Team photo taken before WPI competition in March 2012 in the Bethany Lutheran Church basement in West Hartford. Top row, from left: Amanda Learned, Meredith Durham, Cherice Waller, Anna Sklenar, Danielle Rinnick, Francisca Bustamante, Delaney Patterson, Anna Ybarra, Caitlin Piker, Eric Savage. Bottom row, from left: Robyn DiPietro, Stacey Sklenar, Monica Mohtasham, Mikayla Stricklett, Rachel Silva, Precious Iriaghamo, Kasandra Price, Aimee DiPietro, Patrick Booth, and Renee Jurek.

Figure 4. Anna Sklenar and Sarah Thermer working on robot shooter assembly.

Figure 7. Athena's Warriors—FIRST Robotics Team 3182—at the FIRST Robotics Kick-Off at Farmington High School, Connecticut, in January 2012. Top row, from left: Precious Iriaghamo, Kasandra Price, Francesca Bustamante, Delaney Patterson, Anna Ybarra, Danielle Rinnick, Rachel Silva. Bottom row, from left: Caitlin Piker, Cherice Waller, Anna Sklenar, and Mikayla Stricklett.

Figure 5. Anna Ybarra and Rachel Silva drilling holes and adding pop rivets to the robot arm appendage.

Figure 6. Team members getting ready to go into competition at WPI Regional.

especially in engineering. Although statistics are improving as far as girls and women entering the STEM fields, the number of women engineers is still low compared to their male counterparts. That is reality, and I cannot and will not argue that it will be an issue, but my experience while mentoring this team leads me to conclude something that I myself wouldn't have understood if I hadn't been a part of this team for at least two seasons. The epiphany is that girls need to be nurtured into believing in themselves—that they are as capable as boys of performing the tasks required of them to enter into the STEM fields.

Over the many years that I have worked in technical positions, I have not always, if at all, had the luxury of working beside another woman. I have always affirmed that working among my male counterparts has not been an issue. In some ways, I felt liberated to be among the few women to enter the male-dominated field of engineering. But there is the unspoken truth that it hasn't always been an easy road to be the only woman in the room. At times, it has been a road filled with uncertainty of acceptance from your coworkers and a nagging feeling that your work just is not good enough. Although stereotypes of women's abilities to work in technical fields are quickly fading, I still find instances in my area where girls are being recommended to look at other choices for high school classes besides technical ones, purely because counselors believe they would not want to be the only girl in the classroom.

Perhaps it is a generational ideal or a cultural belief that displaces girls and women from fields that were traditionally held by men. What my experience on the FIRST robotics team has provided me was an understanding that for girls to work to their full potential, whether it be in a technical field or not, they need to know that they can do the job once trained and that they have support from those around them. Yes, the girls on the robotics team will eventually need to start working with males to get a better understanding that it is not an all-girl world out there. What an all-girl team offers is an environment where members can learn engineering principles and not feel so intimidated, with a little more freedom to discover what they are truly capable of doing. They are also getting an appreciation that engineering (STEM fields in general) have no gender, economic, or racial boundaries—just science, and that is how it should be.

For more information on Athena's Warriors, please visit www.team3182.org.

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CALENDAR

2013

20–24 January
MEMS2013: IEEE International Conference on Micro Electro Mechanical Systems. Taipei, Taiwan. http://www.mems2013.org

3–6 March
HRI: ACM/IEEE International Conference on Human-Robot Interaction. Tokyo, Japan. http://humanrobotinteraction.org/2013/

6–10 May
ICRA2013: IEEE International Conference on Robotics & Automation. Karlsruhe, Germany. http://www.icra2013.org

26–28 June
IAV2013: IFAC Symposium on Intelligent Autonomous Vehicles. Brisbane, Australia. http://www.iav2013.org/

9–12 July
AIM2013: IEEE/ASME International Conference on Advanced Intelligent Mechatronics. Wollongong, Australia. http://www.aim2013.org/

4–7 August
ICMA2013: IEEE International Conference on Mechatronics and Automation. Takamatsu, Japan. http://2013.ieee-icma.org/Home/Home.aspx

17–20 August
CASE2013: IEEE International Conference on Automation Science and Engineering. Madison, Wisconsin, USA. http://www.case2013.org/

21–26 October
SSRR2013: IEEE International Symposium on Safety, Security, and Rescue Robtics. Linkoping, Sweden.

3–7 November
IROS2013: IEEE/RSJ International Conference on Intelligent Robots and Systems. Tokyo, Japan. http://www.iros2013.org/

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Date of publication: 6 December 2012

Call for Papers: IEEE Transactions on Robotics
Special Issue on Nanorobotics

Research activities on nanorobotics comprise an emerging interdisciplinary technology area raising new scientific challenges and promising revolutionary advancement in applications such as medicine, biology and industrial manufacturing. Nanorobots could be defined as intelligent systems with overall dimensions at or below the micrometer range that are made of assemblies of nanoscale components while exploiting the physics at such a scale, or as larger platforms capable of robotic operations at the nanoscale. The development of nanorobots presents difficult design, fabrication and control challenges, as such devices will operate in microenvironments whose physical properties differ from those encountered by conventional parts. Furthermore, nanorobotics is a field that calls for collaborative efforts between physicists, chemists, biologists, computer scientists, engineers and other specialists to work towards this common objective.

In an effort to disseminate the current advances in nanorobotics, and to stimulate a discussion on the future research directions in this field, the ***IEEE Transactions on Robotics (T-RO)*** invites papers for a Special Issue in this area. Academic and industry researchers are invited to submit papers on the theoretical, technological and experimental aspects of design, modeling, control and validation of novel nanorobotic devices, with applications in domains including medicine, biology and industrial manufacturing. It is our expectation and goal that this Special Issue will succeed in invigorating research interests towards the development and applications of nanorobotic systems.

Topics - Papers are solicited on all aspects of nanorobotics, including, but not limited to, the following:
•Design of Nanorobots
•Kinematic and Dynamic Modeling of Nanorobotic Systems
•Control of Nanorobotic Systems
•AFM/SPM Based Assembly & Manipulation at the Nanoscale
•Molecular Self-Assembly and Swarm Behavior of Nanorobots
•MRI-based Technologies for Nanorobotics
•Nanoswimmers at low Reynolds Numbers
•Magnetic Wireless Nano-Agents
•Non-Contact Nanorobotics
•Bio-Nano-Robotics
•Applications (e.g. Medicine, Biology, Industrial Manufacturing

Important Dates Nov. 30, 2012: Call for Papers
Mar. 28, 2013: Deadline for Paper Submission
May 30, 2013: Completion of First Review
Aug. 31, 2013:Completion of Final Review
Oct. 27, 2013: Submission of Final Manuscripts
Dec. 2013 (tentative): Publication

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IEEE ROBOTICS & AUTOMATION SOCIETY

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IEEE Transactions on Automation Science and Engineering
CALL FOR PAPERS - SPECIAL ISSUE
Integrated Optimization of Industrial Automation

Lead Guest Editor: Tianyou Chai
Paper Submission Deadline: January 15, 2013   Publication: Fall/Winter 2014

The central theme of the Special Issue will be emerging opportunities and future directions in automation science and engineering for the whole production lines widely seen in various process industries. Examples are the automation in steel making, mineral processing, metal processing, papermaking and petro-chemical plants. The goals of the special issue are to
(1). present the state-of-the-art research in science, engineering and methodologies for automation for the whole production lines, and
(2). provide a forum for experts to disseminate their recent advances and views on future perspectives in this field.

The special issue aims to publish original, significant and visionary automation papers describing scientific methods and technologies that improve planning and scheduling, product quality, production efficiency and energy consumptions. Integrated automation will also be included together with condition monitoring and fault tolerant control for complex industrial processes. Submissions of scientific results from experts in both academia and industry worldwide are strongly encouraged. Topics to be covered include, but are not limited to,

- Planning and scheduling for the whole production lines
- Data driven modeling and operational automation
- Multi-objective operational optimization
- Fault diagnosis and prediction for the whole production lines,
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- Dynamic performance assessment for whole production lines
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