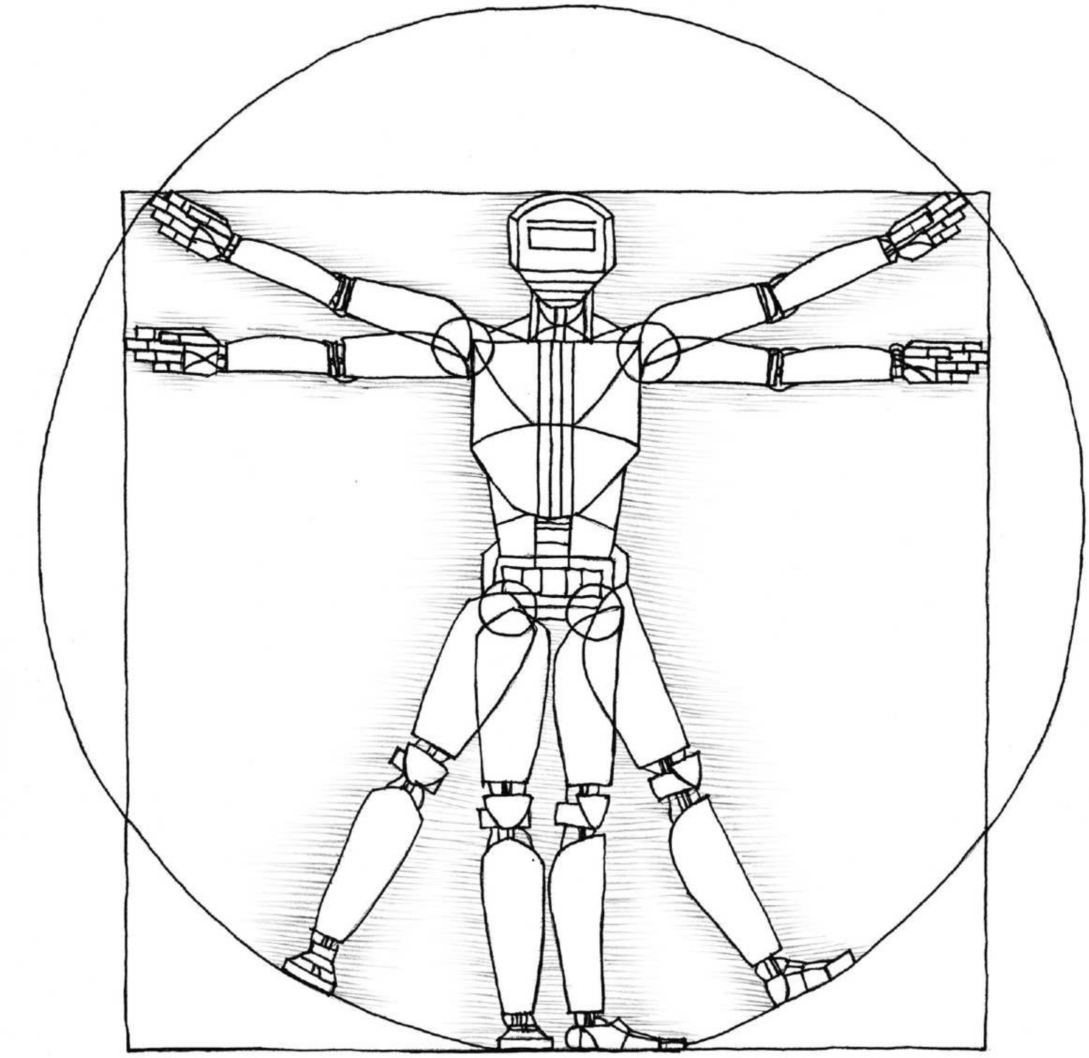
ROBOTICS
SCIENCE AND SYSTEMS



Conference Booklet

August 16-19, 2006
The Hilton Inn at Penn
University of Pennsylvania
Philadelphia, Pennsylvania, USA
www.roboticsconference.org

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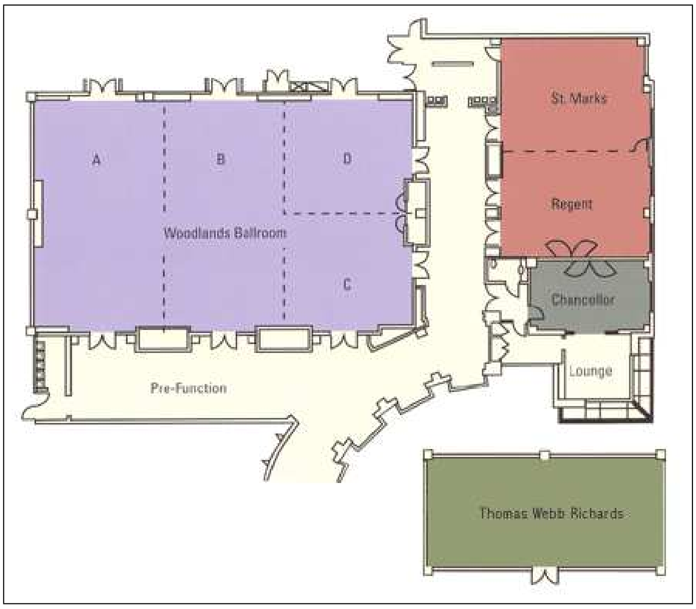
Conference Information

After a successful start, the Robotics Science and Systems (RSS) conference is now headed into its second year. The first conference took place at MIT in June 2005, and drew over 220 attendants. Judging from the preliminary registration figures, RSS 2006 will be larger.

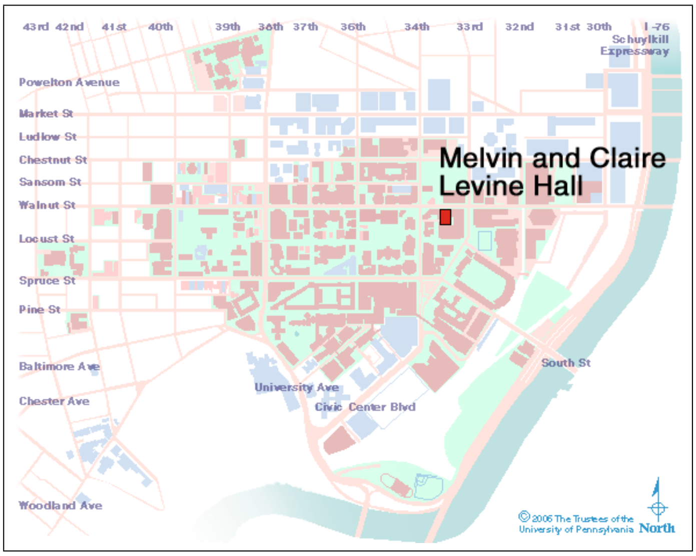
As in 2005, RSS 2006 is a single track, highly selective conference that seeks to showcase the very best research in robotics today. RSS seeks to include all branches of robotics, and to provide a forum at which robotics researchers can exchange some of the most exciting ideas. Since robotics is a fast-moving field, so is RSS. Everyone in the field is encouraged to play an active role in RSS, and to help make RSS a better conference.

Location

All technical sessions, including oral and poster presentations, workshops, and exhibits will take place at the Hilton Inn at Penn, located at 3600 Sansom Street, Philadelphia, PA 19104. Located in the heart of Penn's campus, The Hilton Inn at Penn is a recipient of the AAA Four Diamond rating, and is a 20-minute walk from Philadelphia's downtown Center City district. A map of all conference facilities is shown below.



On Thursday, August 17, from 5:45 p.m. to 7:00 p.m., the GRASP Lab at the University of Pennsylvania welcomes you to a series of demonstrations illustrating an array of projects that are currently under development at GRASP. The demonstrations will take place in the Melvin and Claire Levine Hall, a very short walk from the Hilton Inn at Penn. More information about the demonstrations can be found in your registration packet. The exact location can be found in the map below.



Registration

The Conference Desk will be will be staffed for registration and information services in the pre-function area outside the Woodlands Ballroom on the following schedule:

- Tuesday, August 15 — 5:00PM to 8:00PM (next to hotel reception)
- Wednesday, August 16 — 8:00AM to 5:00PM
- Thursday, August 17 — 8:00AM to 5:00PM
- Friday, August 18 — 8:00AM to 5:00PM
- Saturday, August 19 — 8:00AM to 5:00PM

The conference registration fees are

	Early (before July 15)	Regular (after July 15)
Student	$100	$200
Regular	$300	$400

Both regular and student registration includes attendance to the main conference oral and poster sessions, as well as one half day workshop on Friday, August 18, and one full workshop on Saturday August 19. In addition, it includes one hardcopy of the conference proceedings, and one ticket for the conference banquet at the Kimmel Center for the Performing Arts.

Sponsors

The organizers of Robotics Science and Systems gratefully acknowledge the following conference sponsors

- National Science Foundation
- Naval Research Laboratory
- Microsoft Research
- Boeing Company

We would like to thank all conference sponsors as their support has allowed us to keep registration and workshop fees to a minimum, particularly for graduate students. In addition, the GRASP lab would like to acknowledge partial support from the School of Engineering and Applied Sciences for subsidizing the registration fees of graduate students in the GRASP lab.

Exhibits

Throughout Wednesday, August 16, and Thursday, August 17, the Regent and St. Marks Rooms will host an array of exhibitors. The current list of exhibitors includes:

- Microsoft Research
- Boeing Company
- MIT Press
- Barret Technology
- Evolution Robotics
- Mobile Robots
- Segway LLC
- University of Zaragoza
- Sage Publications
- Kiva Systems

Poster Session and Reception

The poster session will take place on Wednesday, August 16 from 7:00 to 10:00PM. It will take place in the pre-function areas outside the Woodlands Ballroom as well as outside the Regent and St. Mark's room. We encourage all conference attendees to complete their dinner by 7:00PM and skip dessert and coffee since there will be a poster reception including mini dessert pastries, coffee as well as a bar serving wine, beer, and soft drinks.

If you are presenting a poster, please make sure the poster is ready by the time the poster session starts. The poster easels will be available after 12 noon on Wednesday. Please take down your poster at the end of the evening. If you are presenting a spotlight, your two Powerpoint slides will be pre-loaded on our conference laptop. We will unable to switch laptops in this session—*no exceptions*. The spotlight Czars are *Wolfram Burgard* (collecting spotlight slides) and *Vijay Kumar* (chairing the spotlight session). If you did not send your slides to Wolfram yet, but would still like to present, please get in touch with him immediately.

GRASP Demonstration Tour

During the RoboticsScience and Systems conference, the GRASP Laboratory at the University of Pennsylvania would like to welcome you to a series of demonstrations illustrating some of the projects that are currently under development at GRASP. The demonstrations will take place on Thursday, August 17, 5:45PM - 7:00PM and will be held in the Melvin and Claire Levine Hall, home of the GRASP Lab, and a very short walk from the Hilton Inn at Penn.

The demonstrations will take place in two distinct locations in Levine Hall. Some demonstrations will be held in the Main Lobby of the Levine Hall as you enter the building, and others will be held on the 4th floor of Levine Hall, where the GRASP Lab is located. A list of demonstrations with can be found in your registration packet. There will also be a light reception, sponsored by the GRASP Lab.

At the conclusion of the demonstrations, from 7:00-7:30PM buses will depart from the GRASP Lab transferring you to the Kimmel Center for the Performing Arts, home of the Philadelphia Orchestra, and site of the RSS banquet.

Banquet

On Thursday, August 17, there will be a conference banquet at the Kimmel Center for the Performing Arts, located at the corner of Spruce and Broad Streets in downtown Philadelphia. The buffet style banquet is included in the registration fee for all registrants. Your badge will serve as your banquet ticket, so please ensure that you have your badge when boarding the bus. The performance during the banquet will be performed by Dan Paul, Jazz Piano Fellow, University of Pennsylvania (www.danpaulmusic.com). If you would like to bring additional guests to the banquet, please contact the Conference Desk. There is a charge of $100 per person.

Transportation to the banquet will be provided, and buses will depart from the GRASP lab at 7:00PM. At the end of the evening, around 10:00PM, buses will depart from the Kimmel Center and drop you off at either the Hilton Inn at Penn as well as the Rodin College House.

Dormitory Housing

In addition to the conference hotel, we are pleased to offer high rise apartment style accommodations within walking distance of the conference hotel at a rate of $60.00 per person per night for a private bedroom in a multi occupancy apartment. There is minimum 3 night stay requirement and rates are subject to Philadelphia County and City occupancy tax of 14%.

These accommodations are located at the Rodin College House, 3901 Locust Walk, a short walk from the Hilton Inn at Penn. Upon arrival and check-in, guests will receive guest passes at the residence for building access. If you have any questions about dormitory housing, please see the staff at the Conference Desk.

Internet Access

Wireless internet access will be available at the main conference room (Woodlands Ballroom) for no charge. In addition, conference attendees staying at the Hilton Inn at Penn will have internet access in their rooms for a fee.

Lunch and Dinner Breaks

During all conference and workshop days, there will be no breakfast, lunch, or dinner (except for the banquet) provided by the conference. The conference will provide coffee and tea service at the beginning of every day as well as one morning and one afternoon coffee break. In addition, the afternoon coffee break will include an afternoon snack.

We therefore encourage all attendees to plan accordingly taking into consideration the technical schedule of events. Philadelphia has a culturally rich palette of restaurants. Popular dining areas include the Old City neighborhood (especially on Friday night), and the Restaurant Row along Walnut Street from Rittenhouse Square to Broad Street. District. South Philadelphia is home to Philadelphia's Italian population, has great Italian restaurants, and is the birthplace of the Philly cheese steak. The Chinatown area is five blocks away and is packed with Asian restaurants. Another good location for restaurants is around the University of Pennsylvania where you will find good, inexpensive Indian, Thai, Mexican, Japanese and other restaurants. For dinner, we include the following list of restaurants recommended by the local organizers.

UNIVERSITY CITY (AROUND PENN)

- Pod (215-387-1803, Hilton Inn at Penn.) $$$

Cutting edge Japanese/Asian cuisine. Cool lighting and cool food.

- White Dog Cafe (215-386-9224, 3420 Sansom Street) $$$

A classic restaurant on campus blending award-winning cuisine and social activism .

- Nan (215-382-0818, 4000 Chestnut Street) $$

Thai cuisine. A bring your own bottle (BYOB) restaurant.

- Penne (215-823-6222, Hilton Inn at Penn) $$

Italian cuisine with very reasonable wine list.

- Lemon Grass (215-222-8042, 3626 Lancaster Avenue) $$

Thai restaurant. A little farther from Penn, but worth the walk.

- Zocalo (215-895-0139, 3600 Lancaster Avenue) $$

Excellent Mexican/Southwestern cuisine.

- Marathon Grill (40th and Walnut Streets) $

Typical burger place with nice outside seating

CENTER CITY (RITTENHOUSE SQUARE)

- Susanna Foo (215-545-2666, 1512 Walnut St.) $$$$

Famous French-Chinese restaurant. Ask for a table downstairs.

- Brasserie Perrier (568-3000, 1619 Walnut Street) $$$$

Classic and reliable French. More affordable than Perrier's famous Le Bec Fin.

- Alma de Cuba (215-988-1799, 1623 Walnut Street) $$$

Excellent Cuban-inspired food. NY look. Very nice, loud bar.

- Continental Midtown (Chestnut and 18th Streets) $$

See and be seen place. Resonable food, excellent drinks. No reservations.

- Tequila's (215-546-0181, 1602 Locust Street) $$

Happening Mexican restaurant. Nice bar, great tequilas.

- Audrey Claire (215-731-1222, 20th and Spruce Streets) $$

Very pleasant neighborhood restaurant. BYOB. Cash only.

- Monks (215-545-7005, 16th and Spruce Street) $

Best collection of beers in town with good food as well. Very crowded but fun.

CENTER CITY (OLD CITY)

- Morimoto (215-413-9070, 723 Chestnut Street) $$$$

Former Nobu, Iron-chef Morimoto delivers a world class Japanese restaurant.

- Buddakan (215-574-9440, 325 Chestnut Street) $$$

Nouvelle pan asian. Reliably excellent food, fun decor. Go on Fri/Sat night.

- Tangerine (215-627-5116, 232 Market Street) $$$

Great decor, excellent food. Nouvelle Moroccan. Great bar. Go on Saturday night.

- Caf Spice (215-627-6273, 35 S. 2nd Street) $$

Upscale Indian but can be noisy, near the water front.

CENTER CITY (CHINATOWN)

- Vietnam (215-592-1163, 221 N. 11th Street) $$

Possibly the best Vietnamese food in town.

- Penang (215-413-2531, 117 N. 10th Street) $

Malaysian cuisine.

- Rangoon (215-829-8939, 112 N. 9th Street) $

Burmese cuisine.

Transportation

Airport: The SEPTA (Southeastern Pennsylvania Transportation Authority) R1 Rail Line connects the airport to University City (the closest stop to the conference hotel) for approximately $5 per trip. The flat rate for a taxi ride from the University from and to the airport is around $26.25 (plus tip).
Getting around: We do not recommend that you rent a car. Penn and downtown Philadelphia is relatively dense and has an excellent transit system. The Southeastern Pennsylvania Transportation Authority (SEPTA) offers commuter rail service between the city and the suburbs. Buses, subways, and streetcars serve the Center City area. Two subway lines – the Market-Frankford (east-west) and Broad Street (north-south) – crisscross the city.

The best way for a visitor to get around is by taxi. Cabs in downtown are fairly affordable. For short hops from the hotel to "Restaurant Row" or the historic areas, fares would likely be $5-10$. Cabs are particularly cost effective for small groups of 3-4 people.
Parking: For those of you driving to conference, there is no special conference parking available on the Penn campus. The Hilton Inn at Penn offers parking at the garage on the corner of 38th and Sansom Streets, one block from The Hilton Inn At Penn. Public parking is available at various garages. Those most convenient are Lot 34 or garage 37 at 34th and Chestnut Streets, garage 30 at 38th and Walnut Streets, garage 26 at 3201 Walnut Street, and garage 40 at 40th and Walnut Streets. Allow 10-20 minutes for walking to the hotel from these parking lots.

About Philadelphia

Geography: The City of Philadelphia is shaped like the letter Y with the Delaware River to its east separating Pennsylvania from New Jersey and the Schuylkill River Valley along the left branch of the Y. The University City (the area around the University of Pennsylvania and Drexel University) is within a 30 minute walk from Center City (never called downtown). All locations in University City and Center City are at most 10 minute, $10 cab ride away. Philadelphia is within a 2-hour train ride of both New York City and Washington D.C.

Center City and Vicinity: Philadelphia is arguably the most historically rich city in the United States. Visit the area around Market and 6th Streets, where you can find Philadelphia's Independence National Historic Park,where the First Continental Congress met, and where the Declaration of Independence and the United States Constitution were drafted and signed. It is worth visiting the recent National Constitution Center (6th and Market Streets). Philadelphia's Fairmont Parks is the biggest municipal park in the country. It is also worth walking on running on Benjamin Franklin parkway from City Hall (Brooad and Market) to the Philadelphia Museum of Art. Another popular walk is on Walnut Streets, from Rittenhouse Square to Broad Streets, arriving at the theater district.

Museums: The Philadelphia Museum of Art is about a mile from the conference hotel at the opposite end of the Benjamin Franklin Parkway. A large collection of Rodin sculptures is at the Rodin Museum, also located on the Ben Franklin Parkway. There are more Rodin sculptures here than anywhere else except Paris, including a copy of the famous Gates of Hell sculpture.

The University of Pennsylvania Museum, at 34th and Spruce Streets, is home to one of the major archaeological university collections in the USA. It is known for its mummies and relics of Egyptian and Nubian origin.

The Franklin Institute Science Museum, Pennsylvania Academy of the Natural Sciences and the Please Touch Museum are all on Logan Circle (directly in front of the conference venue). The Please Touch Museum is a hands-on museum for children ages one to seven where adults and children explore educational exhibits together. The Franklin Institute has numerous science exhibits and an I-MAX theater; and the Pennsylvania Academy of the Natural Sciences is packed with one of the nation's largest collections of dinosaur fossils.

TECHNICAL PROGRAM AT-A-GLANCE

Technical Program At-A-Glance

Wednesday, August 16th	
8:30-8:40	Opening Remarks
8:40-9:30	**Invited talk:** Hiroshi Ishiguro, Osaka University
9:30-9:55	Technical Session
10:30-11:20	Technical Session
11:20-12:00	**Poster Spotlights**
1:30-2:20	**Invited talk:** Jovan Popovic, Massachusetts Institute of Technology
2:20-3:35	Technical Session
4:00-5:15	Technical Session
7:00-10:00	Poster Session

Thursday, August 17th	
8:30-9:20	**Invited talk:** Takeo Kanade, Carnegie Mellon University
9:20-10:10	Technical Session
10:45-12:00	Technical Session
1:30-2:20	**Invited talk:** Tom Daniel, University of Washington
2:20-3:35	Technical Session
4:00-5:45	Technical Session
5:45-7:00	**GRASP tour**
7:00-10:00	**Conference Banquet** **Speaker**: Ron Kurjanowicz, DARPA

Friday, August 18th	
8:30-9:20	**Invited talk:** Yoshi Nakamura, University of Tokyo
9:20-10:10	Technical Session
10:45-12:00	Technical Session
12:00-12:10	**Closing**
1:30-6:00	Workshops

Saturday, August 19th	
8:30-6:00	Workshops

DETAILED TECHNICAL PROGRAM

Technical Sessions: Wednesday, August 16th, AM

Woodlands Ballroom

8:30-8:40	Opening Remarks
8:40-9:30	**Invited talk:** by Hiroshi Ishiguro, Osaka University
9:30-9:55	*P01: Haptic Playback: Simultaneously Displaying Force and Position Data to Teach Sensorimotor Skills* (see page 29) M. Corno, M. Zefran
9:55-10:30	**Break**
10:30-11:20	*P02: Optimal Rules for Programmed Stochastic Self-Assembly* (see page 29) E. Klavins, S. Burden and N. Napp *P03: Sliding Autonomy for Complex Coordinated Multi-Robot Tasks: Analysis and Experiments* (see page 30) F. Heger, S. Singh
11:20-12:00	**Poster Spotlights**
12:00-1:30	**Lunch**

Technical Sessions: Wednesday, August 16th, PM

Woodlands Ballroom

1:30-2:20 **Invited talk:** Jovan Popovic, Massachusetts Institute of Technology

2:20-3:35 *P04: Improving Robot Navigation Through Self-Supervised Online Learning* (see page 30)
B. Sofman, E. Lin, J. Bagnell, N. Vandapel, A. Stentz

P05: Self-supervised Monocular Road Detection in Desert Terrain (see page 31)
H. Dahlkamp, A. Kaehler, D. Stavens, S. Thrun, G. Bradski

P06: Enhancing Supervised Terrain Classification with Predictive Unsupervised Learning (see page 31)
M. Happold, M. Ollis, N. Johnson

3:35-4:00 **Break**

4:00-5:15 *P07: Distributed Coverage Control with Sensory Feedback for Networked Robots* (see page 32)
M. Schwager, J. McLurkin, D. Rus

P08: Integrated Planning and Control for Convex-bodied Nonholonomic systems using Local Feedback Control Policies (see page 32)
D. Conner, H. Choset, A. Rizzi

P09: On Comparing the Power of Mobile Robots (see page 33)
J. O'Kane, S. LaValle

Poster Session: Wednesday, August 16th

Pre-function area, Woodlands Ballroom, Regent and St. Marks Rooms

7:00-10:00

P27: Computing Smooth Feedback Plans Over Cylindrical Algebraic Decompositions (see page 44)
S. Lindemann, S. LaValle

P28: Analytical Characterization of the Accuracy of SLAM without Absolute Orientation Measurements (see page 44)
A. Mourikis, S. Roumeliotis

P29: The Data Association Kalman Filter (DAKF) (see page 45)
B. Schumitsch, S. Thrun, L. Guibas, K. Olukotun

P30: Adaptive Dynamics with Efficient Contact Handling for Articulated Robots (see page 45)
R. Gayle, M. Lin, D. Manocha

P31: Generation of Point-contact State Space between Strictly Curved Objects (see page 46)
P. Tang, J. Xiao

P32: A Bayesian Approach to Nonlinear Parameter Identification for Rigid Body Dynamics (see page 46)
J. Ting, M. Mistry, J. Peters, S. Schaal, J. Nakanishi

P33: Learning Operational Space Control (see page 47)
J. Peters, S. Schaal

P34: The Iterated Sigma Point Filter with Applications to Long Range Stereo (see page 47)
G. Sibley, G. Sukhatme, L. Matthies

P35: Environment Identification for a Running Robot Using Inertial and Actuator Cues (see page 48)
P. Giguere, G. Dudek, S. Saunderson, C. Prahacs

P36: Elastic Roadmaps: Globally Task-Consistent Motion for Autonomous Mobile Manipulation in Dynamic Environments (see page 48)
Y. Yang, O. Brock

P37: Responsive Robot Gaze to Interaction Partner (see page 49)
Y. Yoshikawa, K. Shinozawa, H. Ishiguro, N. Hagita, T. Miyamoto

P38: Constant-Factor Approximation Algorithms for the Traveling Salesperson Problem for Dubins' Vehicle (see page 49)
K. Savla, E. Frazzoli, F. Bullo

P39: Gaussian Processes for Signal Strength-Based Location Estimation (see page 50)
B. Ferris, D. Haehnel, D. Fox

Technical Sessions: Thursday, August 17th, AM

Woodlands Ballroom

8:30-9:20	**Invited talk:** Takeo Kanade, Carnegie Mellon University
9:20-10:10	*P10: Exploiting Locality in SLAM by Nested Dissection* (see page 33) P. Krauthausen, A. Kipp, F. Dellaert
	P11: Unified Inverse Depth Parametrization for Monocular SLAM (see page 34) J. Montiel, J. Civera, A. Davison
10:10-10:45	**Break**
10:45-12:00	*P12: Qualitative Hybrid Control of Dynamic Bipedal Walking* (see page 34) S. Ramamoorthy, B. Kuipers
	P13: Gait Regulation and Feedback on a Robotic Climbing Hexapod (see page 35) G. Haynes, A. Rizzi
	P14: Slip Prediction Using Visual Information (see page 35) A. Angelova, L. Matthies, D. Helmick, P. Perona
12:00-1:30	**Lunch**

Technical Sessions: Thursday, August 17th, PM

Woodlands Ballroom

1:30-2:20	**Invited talk:** Tom Daniel, University of Washington
2:20-3:35	*P15: Pursuit and Evasion in Arbitrary Dimensions* (see page 36) R. Ghrist, S. Alexander, R. Bishop
	P16: A Unified Framework to Represent Physically Cooperating Mobile Robots and Other Robotic Systems (see page 36) A. Deshpande, J. Luntz
	P17: An Equilibrium Point based Model Unifying Movement Control in Humanoids (see page 37) X. Gu, D. Ballard
3:35-4:00	**Break**
4:00-5:45	*P18: A New Inlier Identification Scheme for Robust Estimation Problems* (see page 37) W. Zhang, J. Kosecka
	P19: A Probabilistic Exemplar Approach to Combine Laser and Vision for Person Tracking (see page 38) D. Schulz
	P20: Outdoor Path Labeling Using Polynomial Mahalanobis Distance (see page 38) G. Grudic, J. Mulligan
	P21: Probabilistic Terrain Analysis For High-Speed Desert Driving (see page 39) S. Thrun, M. Montemerlo, A. Aron
5:45-7:00	**GRASP Tour, Levine Hall**
7:00-10:00	**Conference Banquet, Kimmel Center for the Performing Arts** **Banquet Speaker:** Ron Kurjanowicz, DARPA

Technical Program: Friday, August 18th, AM

Woodlands Ballroom

8:30-9:20	**Invited talk:** Yoshi Nakamura, University of Tokyo
9:20-10:10	*P22: Multi-loop Position Analysis via Iterated Linear Programming* (see page 39) J. Porta, L. Ros, F. Thomas
	P23: Inverse Kinematics for a Serial Chain with Fully Rotatable Joints (see page 40) L. Han, L. Rudolph
10:10-10:45	**Break**
10:45-12:00	*P24: A Gravity Balancing Passive Exoskeleton for the Human Leg* (see page 41) S. Agrawal, S. Banala, A. Fattah
	P25: Design Methodologies for Central Pattern Generators: An Application to Crawling Humanoids (see page 42) L. Righetti, A. Ijspeert
	P26: Dynamic Imitation in a Humanoid Robot through Nonparametric Probabilistic Inference (see page 43) D. Grimes, R. Chalodhorn, R. Rao
12:00-12:05	**Best student paper award presentation** (Sponsored by Springer on behalf of the journal Autonomous Robots)
12:05-12:10	**Closing Remarks**

Workshop Program: Friday, August 18th, PM

FRI1 *Symbolic Approaches to Robot Motion Planning and Control* (see page 55)
Regent and St. Marks Rooms

Calin Belta, Boston University
George J. Pappas, University of Pennsylvania

FRI2 *Robotic Systems for Rehabilitation, Exoskeleton, and Prosthetics* (see page 56)
Woodlands Ballroom A

Yoky Matsuoka, Carnegie Mellon University
Bill Townsend, Barrett Technology, Inc.

FRI3 *Intuitive Human-Robot Interaction for Getting the Job Done* (see page 57)
Woodlands Ballroom B

Geert-Jan M. Kruijff, German Research Center for Artificial Intelligence
Dirk Spenneberg, German Research Center for Artificial Intelligence
Frank Kirchner, German Research Center for Artificial Intelligence

FRI4 *Science and Technology Challenges for Robotics* (see page 58)
Woodlands Ballroom C & D

George Bekey, USC
Vijay Kumar, University of Pennsylvania
Matthew Mason, Carnegie Mellon University

Workshop Program: Saturday, August 19th

SAT1 *Robot Vision for Space Applications* (see page 59)
CANCELED

SAT2 *Socially Assistive Robotics* (see page 59)
St. Marks Room

Adriana Tapus, University of Southern California
Maja Mataric, University of Southern California

SAT3 *Self-Reconfigurable Modular Robots* (see page 60)
Woodlands Ballroom A

Mark Moll, USC/ISI
Behnam Salemi, USC/ISI
Greg Chirikjian, JHU
Eric Klavins, University of Washington
Hod Lipson, Cornell University
Daniela Rus, Massachusetts Institute of Technology
Wei-Min Shen, USC/ISI
Mark Yim, UPenn

SAT4 *Manipulation for Human Environments* (see page 61)
Woodlands Ballroom B

Charles C. Kemp, Massachusetts Institute of Technology
Aaron Edsinger, Massachusetts Institute of Technology
Paul Fitzpatrick, University of Genova
Lorenzo Natale, Massachusetts Institute of Technology
Eduardo Torres-Jara, Massachusetts Institute of Technology

SAT5 *Workshop on the DARPA Grand Challenge:*
Progress and Perspectives in High-Speed Autonomous Robotics (see page 62)
Woodlands Ballroom C & D

Chris Urmson, Carnegie Mellon University
Mike Montemerlo, Stanford
Richard Murray, Caltech
Ron Kurjanowicz, DARPA
Stefano Soatto, UCLA
Sebastian Thrun, Stanford University

SAT6 *Grand Challenges of Micro and Nanoscale Robotics* (see page 63)
Regent Room

Metin Sitti, Carnegie Mellon University
Bradley Nelson, ETH Zurich

PAPER ABSTRACTS

Paper P01 *Haptic Playback: Simultaneously Displaying Force and Position Data to Teach Sensorimotor Skills*

M. Corno, M. Zefran

Abstract: Teaching of sensorimotor skills is often considered one of the most promising applications of haptics. Surgical training and rehabilitation are just some of the areas where such training could have large impact. In many cases, the skill to be taught involves forces that have to be exerted along well defined motion trajectories. However, traditional haptics is not capable of displaying both these modalities simultaneously. This paper proposes a novel engineering analysis of haptic playback, a paradigm that allows to simultaneously display force and position data to a user. The analysis is based on treating the human operator as a multiple-input single-output (MISO) system, where the impact of the visual information through which the position data is displayed is explicitly modeled. An intuitive and simple model for the operator is proposed along with a preliminary validation through studies of human subjects. The model is then used to design a novel control strategy that achieves simultaneous display of force and position data. Subsequently, we present the control-theoretic analysis of the proposed approach and results of experiments with human subjects.

Schedule: see page 17.

Paper P02 *Optimal Rules for Programmed Stochastic Self-Assembly*

E. Klavins, S. Burden and N. Napp

Abstract: In this paper we consider the control of programmable self-assembling systems whose dynamics are governed by stochastic reaction-diffusion dynamics. In our system, particles may decide the outcomes of reactions initiated by the environment thereby steering the global system to produce a desired assembly type. Based on measured natural reaction rates, we describe a method that automatically generates the best program for the parts to use so as to maximize the yield in the system. We demonstrate the design method using theoretical examples as well as on a robotic testbed. Finally, we present a communication protocol that implements the generated programs in a distribute manner.

Schedule: see page 17.

Paper P03 *Sliding Autonomy for Complex Coordinated Multi-Robot Tasks: Analysis and Experiments*

F. Heger, S. Singh

Abstract: Autonomous systems are efficient but often unreliable. In domains where reliability is paramount, efficiency is sacrificed by putting an operator in control via teleoperation. We have investigated a mode of shared control called Sliding Autonomy that combines the efficiency of autonomy and the reliability of human control in the performance of complex tasks, such as the assembly of large structures by teams of robots. Our system is modeled using Markov models to gain a general understanding of the interdependencies between the autonomous robots abilities, those of the operator, and overall system performance. We report results from a study in which three robots work cooperatively with an operator to assemble a structure. Assembly in this case requires high precision and has a large number of failure modes. Our results show that under the Sliding Autonomy paradigm, our combined robot-human team is able to perform the assembly at a level of efficiency approaching that of fully autonomous operation while increasing overall reliability to near-teleoperation levels. This increase in performance is achieved with the additional benefit of significantly reduced mental workload placed on the operator as compared to pure teleoperation. The results of the study support both our expectations and modeling results and show that Sliding Autonomy provides an increase in efficiency over teleoperation together with an increase in reliability over autonomous operation.

Schedule: see page 17.

Paper P04 *Improving Robot Navigation Through Self-Supervised Online Learning*

B. Sofman, E. Lin, J. Bagnell, N. Vandapel, A. Stentz

Abstract: In mobile robotics, there are often features that, while potentially powerful for improving navigation, prove difficult to profit from as they generalize poorly to novel situations. Overhead imagery data, for instance, has the potential to greatly enhance autonomous robot navigation in complex outdoor environments. In practice, reliable and effective automated interpretation of imagery from diverse terrain, environmental conditions, and sensor varieties proves challenging. We introduce an online, probabilistic model to effectively learn to use these scope-limited features by leveraging other features that, while perhaps otherwise more limited, generalize reliably. We apply our approach to provide an efficient, self-supervised learning method that accurately predicts traversal costs over large areas from overhead data. We present results from field testing on-board a robot operating over large distances in off-road environments. Additionally, we show how our algorithm can be used offline to produce a priori traversal cost maps and detect misalignments between overhead data and estimated vehicle positions. This approach can significantly improve the versatility of many unmanned ground vehicles by allowing them to traverse highly varied terrains with increased performance.

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Paper P05 *Self-supervised Monocular Road Detection in Desert Terrain*

H. Dahlkamp, A. Kaehler, D. Stavens, S. Thrun, G. Bradski

Abstract: We present a method for identifying drivable surfaces in difficult unpaved and open terrain conditions as encountered in the DARPA Grand Challenge robot race. Instead of trying to learn an a-priori road appearance model, this method uses laser range finder and pose estimation information to identify a nearby patch of drivable surface and then extrapolates that drivable area outward. Due to power limitations, lasers are only able to see the near range in front of the car. Vision takes a near patch of drivable road found by laser and uses it to construct appearance models to find drivable surface outward into the far range. This information is put into a drivability map for the vehicle path planner. The method was proven by an algorithm scoring framework run on real-world data. Using this system, our robot won the DARPA Grand Challenge and post-race logfile analysis proves that without the computer vision algorithm it could not have driven fast enough to win.

Schedule: see page 18.

Paper P06 *Enhancing Supervised Terrain Classification with Predictive Unsupervised Learning*

M. Happold, M. Ollis, N. Johnson

Abstract: This paper describes a method for classifying the traversability of terrain by combining unsupervised learning of color models that predict scene geometry with supervised learning of the relationship between geometric features and traversability. A neural network is trained offline on hand-labeled geometric features computed from stereo data. An online process learns the association between color and geometry, enabling the robot to assess the traversability of regions for which there is little range information by estimating the geometry from the color of the scene and passing this to the neural network. This online process is continuous and extremely rapid, which allows for quick adaptations to different lighting conditions and terrain changes. The sensitivity of the traversability judgment is further adjusted online by feedback from the robot's bumper. Terrain assessments from the color classifier are merged with pure geometric classifications in an occupancy grid by computing the intersection of the ray associated with a pixel with a ground plane computed from the stereo range data. We present results from DARPA-conducted tests that demonstrate its effectiveness in a variety of outdoor environments.

Schedule: see page 18.

Paper P07 *Distributed Coverage Control with Sensory Feedback for Networked Robots*

M. Schwager, J. McLurkin, D. Rus

Abstract: This paper presents a control strategy that allows a group of robots to position themselves to optimize the measurement of sensory information in the environment. Robots use local information to estimate a sensory scalar field. Their estimate is then used to drive the network to a desirable placement configuration using a decentralized control law. We formulate the problem, provide a practical control solution, and present the results of numerical simulations.We then discuss experiments carried out on a swarm of mobile robots.

Schedule: see page 18.

Paper P08 *Integrated Planning and Control for Convex-bodied Nonholonomic systems using Local Feedback Control Policies*

D. Conner, H. Choset, A. Rizzi

Abstract: We develop a method for defining a hybrid control policy to simultaneously address the global navigation and control problem for a convex-bodied wheeled mobile robot navigating amongst obstacles. The method uses parameterized continuous local feedback control policies that ensure safe operation over local regions of the free configuration space; each local policy is designed to respect nonholonomic constraints, bounds on velocities (inputs), and obstacles in the environment. The hybrid control policy makes use of a collection of these local control policies in concert with discrete planning tools. This approach allows the system to plan, and replan in the face of changing conditions, while preserving the safety and convergence guarantees of the underlying control policies. This work is validated in simulation and experimentally on a convex-bodied wheeled mobile robot. The approach is one of the first that combines formal planning with continuous feedback control guarantees for systems subject to nonholonomic constraints, input bounds, and non-trivial body shape.

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Paper P09 *On Comparing the Power of Mobile Robots*

J. O'Kane, S. LaValle

Abstract: Minimalist models have been studied for a broad array of tasks in robotics. In this paper, we consider the taskcompleting power of robots in terms of the sensors and actuators with which the robot is equipped. Our goal is to understand the relative power of different sets of sensors and actuators and to determine which of these sets enable the robot to complete its task. We define robots as collections of robotic primitives and provide a formal method for comparing the sensing and actuation power of robots constructed from these primitives. This comparison, which is based on the how the robots progress through their information spaces, induces a partial order over the set of robot systems. We prove some basic properties of this partial order and then apply it to a limited-sensing version of the global localization problem.

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Paper P10 *Exploiting Locality in SLAM by Nested Dissection*

P. Krauthausen, A. Kipp, F. Dellaert

Abstract: In this paper we investigate how a nested dissection ordering method can improve the performance of smoothing SLAM. The computational complexity of SLAM is dominated by the cost of factorizing a matrix of all measurements into a square root form, which has cubic complexity in the worst case. We show that the computational complexity for the factorization of typical measurement matrices occurring in the SLAM problem can be bound tighter under reasonable assumptions.

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Paper P11 *Unified Inverse Depth Parametrization for Monocular SLAM*

J. Montiel, J. Civera, A. Davison

Abstract: Recent work has shown that the probabilistic SLAM approach of explicit uncertainty propagation can succeed in permitting repeatable 3D real-time localization and mapping even in the 'pure vision' domain of a single agile camera with no extra sensing. An issue which has caused difficulty in monocular SLAM however is the initialization of features, since information from multiple images acquired during motion must be combined to achieve accurate depth estimates. This has led algorithms to deviate from the desirable Gaussian uncertainty representation of the EKF and related probabilistic filters during special initialization steps. In this paper we present a new unified parametrization for point features within monocular SLAM which permits efficient and accurate representation of uncertainty during undelayed initialisation and beyond, all within the standard EKF (Extended Kalman Filter). The key concept is direct parametrization of inverse depth, where there is a high degree of linearity. Importantly, our parametrization can cope with features which are so far from the camera that they present little parallax during motion, maintaining sufficient representative uncertainty that these points retain the opportunity to 'come in' from infinity if the camera makes larger movements. We demonstrate the parametrization using real image sequences of large-scale indoor and outdoor scenes.

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Paper P12 *Qualitative Hybrid Control of Dynamic Bipedal Walking*

S. Ramamoorthy, B. Kuipers

Abstract: We present a qualitative approach to the dynamical control of bipedal walking that allows us to combine the benefits of passive dynamic walkers with the ability to walk on uneven terrain. We demonstrate an online control strategy, synthesizing a stable walking gait along a sequence of irregularly spaced stepping stones. The passive dynamic walking paradigm has begun to establish itself as a useful approach to gait synthesis. Recently, researchers have begun to explore the problem of actuating these passive walkers, to extend their domain of applicability. The problem of applying this approach to applications involving uneven terrain remains unsolved and forms the focus of this paper. We demonstrate that through the use of qualitative descriptions of the task, the use of the nonlinear dynamics of the robot mechanism and a multiple model control strategy, it is possible to design gaits that can safely operate under realistic terrain conditions.

Schedule: see page 20.

Paper P13 *Gait Regulation and Feedback on a Robotic Climbing Hexapod*

G. Haynes, A. Rizzi

Abstract: This paper proposes a novel method of applying feedback control for legged robots, by directly modifying parameters of a robots gait pattern. Gaits are a popular means of producing stable locomotion on legged robots, through the use of cyclic feedforward motion patterns, while requiring little to no sensory information. We are interested, however, in incorporating feedback with these systems, and attempt to use salient key parameters, found in gait patterns, to produce behaviors that span the space of possible gaits. These concepts are applied to a robotic hexapod, which, through the use of compliant microspines on its feet, is capable of climbing hard vertical textured surfaces, such as stucco. Experimental results are obtained comparing the use of a purely feedforward gait pattern to a behavior that actively modifies gait parameters while climbing, based upon sensory data.

Schedule: see page 20.

Paper P14 *Slip Prediction Using Visual Information*

A. Angelova, L. Matthies, D. Helmick, P. Perona

Abstract: This paper considers prediction of slip from a distance for wheeled ground robots using visual information as input. Large amounts of slippage which can occur on certain surfaces, such as sandy slopes, will negatively affect rover mobility. Therefore, obtaining information about slip before entering a particular terrain can be very useful for better planning and avoiding terrains with large slip. The proposed method is based on learning from experience and consists of terrain type recognition and nonlinear regression modeling. After learning, slip prediction is done remotely using only the visual information as input. The method has been implemented and tested ofine on several off-road terrains including: soil, sand, gravel, and woodchips. The slip prediction error is about 20 of the step size.

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Paper P15 *Pursuit and Evasion in Arbitrary Dimensions*

R. Ghrist, S. Alexander, R. Bishop

Abstract: Most results in pursuit-evasion games apply only to planar domains or perhaps to higher-dimensional domains which must be convex. We introduce a very general set of techniques to generalize and extend certain results on simple pursuit to non-convex domains of arbitrary dimension which satisfy a coarse curvature condition (the CAT(0) condition).

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Paper P16 *A Unified Framework to Represent Physically Cooperating Mobile Robots and Other Robotic Systems*

A. Deshpande, J. Luntz

Abstract: There is a need to develop a methodology to model physically cooperating mobile robots so as to systematically design and analyze such systems. Our approach is to treat the linked mobile robots as a multiple degree-of-freedom object, comprising an articulated open kinematic chain, which is being manipulated by pseudo robots (p-robots) at the ground interaction points. Dynamics of the open chain are computed independently of the constraints, thus allowing the same set of equations to be used as the constraint conditions change, and simplifying the addition of multiple robots to the chain. The decoupling achieved through constraining the p-robots facilitates the analysis of kinematic as well as force constraints, not possible with direct analysis. We introduce the idea of a tipping cone, similar to a standard friction cone, to test whether forces on the robots cause undesired tipping. We have carried out static as well as dynamic analysis for a 2-robot cooperation case. Also, we have demonstrated that introduction of redundant actuation, by an additional third robot, can help in improving the friction requirements. We also present our preliminary ideas for employing this newly designed framework to analyze other interesting multi-body robotic systems.

Schedule: see page 21.

Paper P17 *An Equilibrium Point based Model Unifying Movement Control in Humanoids*

X. Gu, D. Ballard

Abstract: Despite all the dynamics methods effectively used in robotics control, few tackle the intricacies of the human musculoskeletal system itself. During movements, a huge amount of energy can be stored passively in the biomechanics of the muscle system. Controlling such a system in a way that takes advantage of the stored energy has lead to the Equilibrium-point hypothesis (EPH). In this paper, we propose a two-phase model based on the EPH. Our model is simple and general enough to be extended to various motions over all body parts. In therst phase, gradient descent is used to obtain one kinematics endpoint in joint space, given a task in Cartesian space. In the second phase where the movements are actually executed, we use damped springs to simulate muscles to drive the limb joints. The model is demonstrated by a humanoid doing walking, reaching, and grasping.

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Paper P18 *A New Inlier Identification Scheme for Robust Estimation Problems*

W. Zhang, J. Kosecka

Abstract: Common goal of many computer vision and robotics algorithms is to extract geometric information from the sensory data. Due to the presence of the sensor noise and errors in matching or segmentation, the available data are often corrupted with outliers. In such instances, the problem of estimation of parametric models needs to be tackled by robust estimation methods. In the presence of large fraction of outliers sampling based methods are often employed to tackle the task. When the fraction of the outliers is significant and the parametric model is complex, the traditionally used RANSAC algorithm requires large number of samples, prior knowledge of the outlier ratio and additional, difficult to obtain, inlier threshold for hypothesis evaluation. To tackle these problems we propose a novel and efficient sampling based method for robust estimation of model parameters from redundant data. The method is based on the observation that for each data point, the properties of the distribution of the residuals with respect to the generated hypotheses reveal whether the point is an outlier or inlier. The problem of inlier/outlier identification can then be formulated as a classification problem. The proposed method is demonstrated on motion estimation problems from with large percentage of outliers (70%) on both synthetic and real data and estimation of planar models from range data. The method is shown to be of an order of magnitude more efficient than currently existing methods and does not require prior knowledge of an outlier ratio and inlier threshold.

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Paper P19 *A Probabilistic Exemplar Approach to Combine Laser and Vision for Person Tracking*

D. Schulz

Abstract: This article presents an approach to person tracking that combines camera images and laser range data. The method uses probabilistic exemplar models, which represent typical appearances of persons in the sensor data by metric mixture distributions. Our approach learns such models for laser and for camera data and applies a Rao-Blackwellized particle filter in order to track a persons appearance in the data. The filter samples joint exemplar states and tracks the persons position conditioned on the exemplar states using a Kalman filter. We describe an implementation of the approach based on contours in images and laser point set features. Additionally, we show how the models can be learned from training data using clustering and EM. Finally, we give first experimental results of the method which show that it is superior to purely laser-based approaches for determining the position of persons in images.

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Paper P20 *Outdoor Path Labeling Using Polynomial Mahalanobis Distance*

G. Grudic, J. Mulligan

Abstract: Autonomous robot navigation in outdoor environments remains a challenging and unsolved problem. A key issue is our ability to identify safe or navigable paths far enough ahead of the robot to allow smooth trajectories at acceptable speeds. Colour or texture-based labeling of safe path regions in image sequences is one way to achieve this far field prediction. A challenge for classifiers identifying path and nonpath regions is to make meaningful comparisons of feature vectors at pixels or over a window. Most simple distance metrics cannot use all the information available and therefore the resulting labeling does not tightly capture the visible path. We introduce a new Polynomial Mahalanobis Distance and demonstrate its ability to capture the properties of an initial positive path sample and produce accurate path segmentation with few outliers. Experiments show the method's effectiveness for path segmentation in natural scenes using both colour and texture feature vectors. The new metric is compared with classifications based on Euclidean and standard Mahalanobis distance and produces superior results.

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Paper P21 *Probabilistic Terrain Analysis For High-Speed Desert Driving*

S. Thrun, M. Montemerlo, A. Aron

Abstract: The ability to perceive terrain is a key problem in mobile robot navigation. Terrain perception problems arise in planetary robotics, agriculture, mining, and, of course, selfdriving cars. Here, we introduce the PTA (probabilistic terrain analysis) algorithm for terrain classification with a fastmoving robot platform. The PTA algorithm uses probabilistic techniques to integrate range measurements over time, and relies on efficient statistical tests for distinguishing drivable from nondrivable terrain. By using probabilistic techniques, PTA is able to accommodate severe errors in sensing, and identify obstacles with nearly 100% accuracy at speeds of up to 35mph. The PTA algorithm was an essential component in the DARPA Grand Challenge, where it enabled a robot to traverse the entire course in record time.

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Paper P22 *Multi-loop Position Analysis via Iterated Linear Programming*

J. Porta, L. Ros, F. Thomas

Abstract: This paper presents a numerical method able to isolate all configurations that an arbitrary loop linkage can adopt, within given ranges for its degrees of freedom. The procedure is general, in the sense that it can be applied to single or multiple intermingled loops of arbitrary topology, and complete, in the sense that all possible solutions get accurately bounded, irrespectively of whether the analyzed linkage is rigid or mobile. The problem is tackled by formulating a system of linear, parabolic, and hyperbolic equations, which is here solved by a new strategy exploiting its structure. The method is conceptually simple, geometric in nature, and easy to implement, yet it provides solutions at the desired accuracy in short computation times.

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Paper P23 *Inverse Kinematics for a Serial Chain with Fully Rotatable Joints*

L. Han, L. Rudolph

Abstract: Inverse kinematics (IK) problems are important in the study of robotics and have found applications in other fields such as structural biology. The conventional formulation of IK in terms of joint parameters amounts to solving a system of nonlinear equations, which is considered to be very hard for general chains, especially for those with many links. In this paper, we study IK for a serial chain with maximal DOF rotational joints, in particular, either a spatial chain with spherical joints, or a planar chain with revolute joints, and without considering other constraints such as the joint limits and link collision-free constraints, a common approach taken in the study of inverse kinematics. We present a new set of geometric parameters for such chains, which are not joint angles, and use a novel approach to formulate the inverse kinematics as a system of linear inequalities, which is an exact, not an approximate, formulation of the IK problem. It follows that the IK problem for a chain with an arbitrary number of joints can be done efficiently in many ways including linear programming. Under our new formulation, the set of solutions for an IK problem (as specified by a configuration of the end link), and more generally the set of solutions for all IK problems, is essentially piecewise convex. Our approach can also be generalized to other linkages such as those with prismatic joints sandwiched between rotational joints and with multiple loops that have a tree decomposition of triangles. The efficient algorithms and nice geometry entailed by piecewise convexity considerably simplify IK related problems, including motion planning, in the systems under study, and thus broaden the class of practical mechanisms at the disposal of robot designers.

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Paper P24 *A Gravity Balancing Passive Exoskeleton for the Human Leg*

S. Agrawal, S. Banala, A. Fattah

Abstract: A gravity balancing lower extremity exoskeleton is a simple mechanical device composed of rigid links, joints and springs, which is adjustable to the geometry and inertia of the leg of a human subject wearing it. This passive exoskeleton does not use any motors or controllers, yet can still unload the human leg joints of the gravity load over the full range of motion of the leg. The underlying principle of gravity balancing consists of two steps: (i) Locate the combined system center of mass of the human leg and the exoskeleton, (ii) Add springs to the exoskeleton, one between the center of mass of the combined system and the fixed frame representing the trunk, the others within the links of the exoskeleton so that the potential energy of the combined system is invariant with configuration of the leg. Additionally, parameters of the exoskeleton can be changed to achieve a prescribed level of partial balancing, between 0-gravity and 1-gravity. The goals of this paper are as follows: (i) briefly review the theory for gravity balancing and present laboratory prototypes of gravity balanced machines, (ii) describe the design of a lower extremity exoskeleton that was fabricated using this principle, and (iii) show the performance of the exoskeleton on both healthy human subjects and a stroke patient by comparison of leg muscle EMG recordings, joint range of motion, and measured joint torques. These results strongly suggest that human joints can be unloaded from gravity using these exoskeletons and the human joint range of motion can be significantly increased. Potential applications of gravity balancing exoskeletons include: (i) gait training of stroke patients, (ii) characterization of long-term effects of zero gravity on the human musculature, (iii) human performance augmentation during assembly tasks.

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Paper P25 *Design Methodologies for Central Pattern Generators: An Application to Crawling Humanoids*

L. Righetti, A. Ijspeert

Abstract: Systems of coupled nonlinear oscillators inspired from animal central pattern generators (CPGs) are increasingly used for the control of locomotion in robots, in particular for online trajectory generation. Indeed, such systems present interesting characteristics like limit cycle behavior (i.e. stability), synchronization, and the possibility to be entrained and modulated by external signals. There are now good methodologies for designing systems that exhibit specific gaits, i.e. specific phase relations between oscillators, however techniques to modulate the shape of the rhythmic signals in a controlled way are still missing. In this article, we present a method for shaping the signals of a oscillatory system according to several criteria that are relevant for locomotion control (but which could also be useful for other applications). These criteria include being able to adjust the relative durations of ascending and descending phases in a cycle, and to temporarily modulate the dynamics of one oscillator according to the states of another one. The first criterion is important for locomotion in order to adjust the duration of swing and stance phases, while the second allows one to introduce signal shape variations to deal with proper inter-limb coordination. We apply the method to the design of a system of coupled oscillators used to control crawling in a simulated humanoid robot. Using some key characteristics of signal shapes extracted from recordings of baby crawling, we design the system to produce stable trot-like crawling gaits. Insights from symmetry groups theory are used to design the right phase lags. The oscillators are designed such that the speed of locomotion can be adjusted by varying the duration of the stance phase while keeping the duration of the swing phase constant, like in most tetrapod animals.

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Paper P26 *Dynamic Imitation in a Humanoid Robot through Nonparametric Probabilistic Inference*

D. Grimes, R. Chalodhorn, R. Rao

Abstract: We tackle the problem of learning imitative wholebody motions in a humanoid robot using probabilistic inference in Bayesian networks. Our approach exploits the rich prior information obtained from human motion capture data for dynamic imitation. Dynamic imitation implies that the robot must interact with its environment and account for forces such as gravity and inertia during imitation. Rather than explicitly modeling these forces and the body of the humanoid as in traditional approaches, we show that imitative motion can be achieved by learning a sensor-based representation of dynamic balance. Bayesian networks provide a sound theoretical framework for combining both the kinematic prior information from observing a human demonstrator and the dynamic prior information which, with high probability will keep the motion dynamically balanced during imitation. By posing the problem as one of inference in a Bayesian network, we show that methods developed for approximate inference can be leveraged to efficiently perform inference of actions. Additionally, by using nonparametric inference and a nonparametric (Gaussian process) forward model, our approach does not make any strong assumptions about the physical environment or the mass and inertial properties of the humanoid robot. We propose an iterative, probabilistically constrained algorithm for exploring the space of motor commands and show that the algorithm can quickly discover dynamically stable actions for whole-body imitation of human motion. Experimental results based on simulation and subsequent execution by a real Hoap-2 humanoid robot demonstrate that our algorithm is able to imitate a human performing actions such as squatting and a one-legged balance.

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Paper P27 *Computing Smooth Feedback Plans Over Cylindrical Algebraic Decompositions*

S. Lindemann, S. LaValle

Abstract: In this paper, we construct smooth feedback plans over cylindrical algebraic decompositions. Given a cylindrical algebraic decomposition on Rn, a goal state xg, and a connectivity graph of cells reachable from the goal cell, we construct a vector field that is smooth everywhere except on a set of measure zero and the integral curves of which are smooth (i.e., C1) and arrive at a neighborhood of the goal state in finite time. We call a vector field with these properties a smooth feedback plan. The smoothness of the integral curves guarantees that they can be followed by a system with finite acceleration inputs: x = u. We accomplish this by defining vector fields for each cylindrical cell and face and smoothly interpolating between them. Schwartz and Sharir showed that cylindrical algebraic decompositions can be used to solve the generalized piano movers problem, in which multiple (possibly linked) robots described as semi-algebraic sets must travel from their initial to goal configurations without intersecting each other or a set of semi-algebraic obstacles. Since we build a vector field over the decomposition, this implies that we can obtain smooth feedback plans for the generalized piano movers problem.

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Paper P28 *Analytical Characterization of the Accuracy of SLAM without Absolute Orientation Measurements*

A. Mourikis, S. Roumeliotis

Abstract: In this paper we derive analytical upper bounds on the covariance of the state estimates in SLAM. The analysis is based on a novel formulation of the SLAM problem, that enables the simultaneous estimation of the landmark coordinates with respect to the a robot-centered frame (relative map), as well as with respect to a fixed global frame (absolute map). A study of the properties of the covariance matrix in this formulation yields analytical upper bounds for the uncertainty of both map representations. Moreover, by employing results from Least Squares estimation theory, the guaranteed accuracy of the robot pose estimates is derived as a function of the accuracy of the robots sensors, and of the properties of the map. Contrary to previous approaches, the method presented here makes no assumptions about the availability of a sensor measuring the absolute orientation of the robot. The theoretical analysis is validated by simulation results and real-world experiments.

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Paper P29 *The Data Association Kalman Filter (DAKF)*

B. Schumitsch, S. Thrun, L. Guibas, K. Olukotun

Abstract: Tracking posteriors estimates for problems with data association uncertainty is one of the big open problems in the literature on filtering and tracking. This paper presents a new filter for online tracking of many individual objects with data association ambiguities. It tightly integrates the continuous aspects of the problem locating the objects with the discrete aspects the data association ambiguity. The key innovation is a probabilistic information matrix that links entities with internal tracks of the filter, enabling it to maintain a full posterior over the system amid data association uncertainties. The filter scales quadratically in complexity, just like a conventional Kalman filter. We derive the algorithm formally from first principles (Bayes rule), and present results using a real-world camera array and a large scale sensor network simulation.

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Paper P30 *Adaptive Dynamics with Efficient Contact Handling for Articulated Robots*

R. Gayle, M. Lin, D. Manocha

Abstract: We present a novel adaptive dynamics algorithm with efficient contact handling for articulated robots. Our algorithm automatically computes a fraction of the joints whose motion provides a good approximation to overall robot dynamics. We extend Featherstone's Divide-and-Conquer algorithm and are able to efficiently handle all contacts and collisions with the obstacles int he environment. Overall, our approach provides a time-critical collision detection and resolution algorithm for highly articulated bodies and its complexity is sub-linear in the number of degrees-of-freedom. We demonstrate our algorithm on several complex articulated robots consisting of hundreds of joints.

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Paper P31 *Generation of Point-contact State Space between Strictly Curved Objects*

P. Tang, J. Xiao

Abstract: Isolated point contacts are most common between two curved objects that do not have line segment on their surfaces. This paper addresses how to represent concisely and generate automatically graphs of topological contact states made of isolated contact points between such curved objects. Information of contact states is useful for a wide range of applications,from robotic tasks involving compliant motion to virtual prototyping, haptic rendering, and dynamic simulation. The approach has been implemented with an effective algorithm.

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Paper P32 *A Bayesian Approach to Nonlinear Parameter Identification for Rigid Body Dynamics*

J. Ting, M. Mistry, J. Peters, S. Schaal, J. Nakanishi

Abstract: For robots of increasing complexity such as humanoid robots, conventional identification of rigid body dynamics models based on CAD data and actuator models becomes difficult and inaccurate due to the large number of additional nonlinear effects in these systems, e.g., stemming from stiff wires, hydraulic hoses, protective shells, skin, etc. Data driven parameter estimation offers an alternative model identification method, but it is often burdened by various other problems, such as significant noise in all measured or inferred variables of the robot. The danger of physically inconsistent results also exists due to unmodeled nonlinearities or insufficiently rich data. In this paper, we address all these problems by developing a Bayesian parameter identification method that can automatically detect noise in both input and output data for the regression algorithm that performs system identification. A post-processing step ensures physically consistent rigid body parameters by nonlinearly projecting the result of the Bayesian estimation onto constraints given by positive definite inertia matrices and the parallel axis theorem. We demonstrate on synthetic and actual robot data that our technique performs parameter identification with 10 to 30% higher accuracy than traditional methods. Due to the resulting physically consistent parameters, our algorithm enables us to apply advanced control methods that algebraically require physical consistency on robotic platforms.

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Paper P33 *Learning Operational Space Control*

J. Peters, S. Schaal

Abstract: While operational space control is of essential importance for robotics and well-understood from an analytical point of view, it can be prohibitively hard to achieve accurate control in face of modeling errors, which are inevitable in complex robots, e.g., humanoid robots. In such cases, learning control methods can offer an interesting alternative to analytical control algorithms. However, the resulting learning problem is ill-defined as it requires to learn an inverse mapping of a usually redundant system, which is well known to suffer from the property of non-covexity of the solution space, i.e., the learning system could generate motor commands that try to steer the robot into physically impossible configurations. A first important insight for this paper is that, nevertheless, a physically correct solution to the inverse problem does exits when learning of the inverse map is performed in a suitable piecewise linear way. The second crucial component for our work is based on a recent insight that many operational space controllers can be understood in terms of a constraint optimal control problem. The cost function associated with this optimal control problem allows us to formulate a learning algorithm that automatically synthesizes a globally consistent desired resolution of redundancy while learning the operational space controller. From the view of machine learning, the learning problem corresponds to a reinforcement learning problem that maximizes an immediate reward and that employs an expectation-maximization policy search algorithm. Evaluations on a three degrees of freedom robot arm illustrate the feasability of our suggested approach.

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Paper P34 *The Iterated Sigma Point Filter with Applications to Long Range Stereo*

G. Sibley, G. Sukhatme, L. Matthies

Abstract: This paper investigates the use of statistical linearization to improve iterative non-linear least squares estimators. In particular, we look at improving long range stereo by filtering feature tracks from sequences of stereo pairs. A novel filter called the iterated Sigma Point Kalman Filter (ISPKF) is developed from first principles; this filter is shown to achieve superior performance in terms of efficiency and accuracy when compared to the Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), and Gauss-Newton filter. We also compare the ISPKF to the optimal Batch filter and to a Gauss-Newton Smoothing filter. For the long range stereo problem the ISPKF comes closest to matching the performance of the full batch MLE estimator. Further, the ISPKF is demonstrated on real data in the context of modeling environment structure from long range stereo data.

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Paper P35 *Environment Identification for a Running Robot Using Inertial and Actuator Cues*

P. Giguere, G. Dudek, S. Saunderson, C. Prahacs

Abstract: In this paper, we explore the idea of using inertial and actuator information to accurately identify the environment of an amphibious robot. In particular, in our work with a legged robot we use internal sensors to measure the dynamics and interaction forces experienced by the robot. From these measurements we use simple machine learning methods to probabilistically infer properties of the environment, and therefore identify it. The robots gait can then be automatically selected in response to environmental changes. Experimental results show that for several environments (sand, water, snow, ice, etc.), the identification process is over 90 per cent accurate. The requisite data can be collected during a half-leg rotation (about 250 ms), making it one of the fastest and most economical environment identifiers for a dynamic robot. For the littoral setting, a gaitchange experiment is done as a proof-of-concept of a robot automatically adapting its gait to suit the environment.

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Paper P36 *Elastic Roadmaps: Globally Task-Consistent Motion for Autonomous Mobile Manipulation in Dynamic Environments*

Y. Yang, O. Brock

Abstract: The autonomous execution of manipulation tasks in unstructured, dynamic environments requires the consideration of various motion constraints. Any motion performed during the manipulation task has to satisfy constraints imposed by the task itself, but also has to consider kinematic and dynamic limitations of the manipulator, avoid unpredictably moving obstacles, and observe constraints imposed by the global connectivity of the workspace. Furthermore, the unpredictability of unstructured environments requires the continuous incorporation of feedback to reliably satisfy these constraints. We present a novel feedback motion planning approach, called elastic roadmap framework, capable of satisfying all of the motion constraints that arise in autonomous mobile manipulation and their respective feedback requirements. This framework is validated with simulation experiments using a mobile manipulation platform and a stationary manipulator.

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Paper P37 *Responsive Robot Gaze to Interaction Partner*

Y. Yoshikawa, K. Shinozawa, H. Ishiguro, N. Hagita, T. Miyamoto

Abstract: Gaze is regarded as playing an important role in face-to-face communication, for example exhibiting ones attention and regulating turn-taking during conversation, and therefore has been one of central topics in several fields including psychology, human-computer and human-robot interaction studies. Although a lot of findings in psychology have encouraged the previous work in both human-computer and human-robot interaction studies, how to move the agents gaze, including when to move it, has not been explored yet, and therefore is addressed in this study. The impression a person forms from an interaction is strongly influenced by the degree to which their partners gaze direction is correlates with their own. In this paper, we propose methods of responsive robot gaze control and confirm their effect on the feeling of being looked at, which is considered to be the basis of impression conveyance with gaze, through face-to-face interaction experiments.

Schedule: see page 19.

Paper P38 *Constant-Factor Approximation Algorithms for the Traveling Salesperson Problem for Dubins' Vehicle*

K. Savla, E. Frazzoli, F. Bullo

Abstract: This paper proposes the first known algorithm that achieves a constant-factor approximation of the minimum length tour for a Dubins vehicle through n points on the plane. By Dubins vehicle, we mean a vehicle constrained to move at constant speed along paths with bounded curvature without reversing direction. For this version of the classic Traveling Salesperson Problem, our algorithm closes the gap between previously established lower and upper bounds; the achievable performance is of order $n^{2/3}$. Additionally, we consider the following dynamic scenario: given a stochastic process that generates target points over time, how does one steer the Dubins vehicle to stabilize the system, in the sense that the number of unvisited targets does not diverge over time? For this scenario, we propose the first known receding-horizon strategy which is indeed stabilizing and whose performance is within a constant factor from the optimum, for all target generation rates.

Schedule: see page 19.

Paper P39 *Gaussian Processes for Signal Strength-Based Location Estimation*

B. Ferris, D. Haehnel, D. Fox

Abstract: Estimating the location of a mobile device or a robot from wireless signal strength has become an area of highly active research. The key problem in this context stems from the complexity of how signals propagate through space, especially in the presence of obstacles such as buildings, walls or people. In this paper we show how Gaussian processes can be used to generate a likelihood model for signal strength measurements. We also show how parameters of the model, such as signal noise and spatial correlation between measurements, can be learned from data via hyperparameter estimation. Experiments using WiFi indoor data and GSM cellphone connectivity demonstrate the superior performance of our approach.

Schedule: see page 19.

WORKSHOPS

Workshop FRI1 *Symbolic Approaches to Robot Motion Planning and Control*
Regent and St. Marks Rooms

Calin Belta, Boston University
George J. Pappas, University of Pennsylvania

URL: http://iasi.bu.edu/∼cbelta/rss06_wsa/

Description:
Planning and control of single and multi-agent robotic systems is a very challenging problem that received a lot of attention in recent years. The goal is to be able to specify a task in a high level language and have the robot(s) automatically convert this specification into a set of low level primitives (such as feedback controllers) to accomplish the task. The challenge in this area is the development of a computationally efficient framework accommodating both the complexity of the environment and the robot control and communication constraints, while allowing for a 'rich' specification language. With few exceptions, most of the works in this area focus on either the complexity of the environment (and assume that the robots have trivial dynamics or kinematics) or on the detailed robot dynamics (while assuming trivial environments). The works studying communication architectures in multi-robot systems are focused on proving that certain local interactions can give rise to interesting global behaviors. However, the inverse problem of generating local rules from non-trivial high level specifications of the group is still not understood. Finally, in most of the existing works, the motion planning problem is simply specified as "go from A to B". This is either too explicit, or simply does not capture the nature of the task, which might require logical (e.g., "visit either A or B") and/or temporal operators ("reach A and then B infinitely often").
Covered topics: In the first part of the workshop, we will discuss recent results advocating the use of temporal logics as high level specification languages for robotic systems. Specifically, we will first consider the problem of automatic planning and provably correct control of one robot from temporal logic formulas in predicates over environmental coordinates (Pappas) and the problem of executing such a specification by a small group of robots or by an arbitrarily large robotic swarm (Belta). We will then study the problem of defining local interaction rules so that the dynamics of a network modeling robot self assembly obey a performance specification given in terms of the probability of satisfaction of a temporal property (Klavins). In the above, the motion plan is obtained through model checking, and results in the form of a string (word) over input (control) modes. In the second part of the workshop, we will focus on the explicit design of such a string. We will first discuss this approach from the point of view of computational complexity and closeness to desired specifications given in continuous space (Bicchi). We will then present a divide-and-conquer approach for the identification of control modes and their combination into strings, with emphasis on reusability, expressiveness, and correctness (Egerstedt). Finally, we will focus on a method of designing and combining motion primitives into strings, which exploits the symmetries inherent in robotic systems (Frazzoli). While geared towards slightly different aspects of the robot planning and control problem, all the above approaches are based on the idea that complexity in robotic systems can be dealt with by (formally) abstracting continuous information into (discrete) finite symbolic descriptions, which are amenable for expressive specification languages and powerful analysis algorithms.

Workshop FRI2 *Robotic Systems for Rehabilitation, Exoskeleton, and Prosthetics*
Woodlands Ballroom A

Yoky Matsuoka, Carnegie Mellon University
Bill Townsend, Barrett Technology, Inc.

URL: http://www.cs.cmu.edu/∼yoky/rss/

Description:
Due to advances in modern medicine, the elderly population is growing worldwide. Along with this growth, there is a growing need for physical rehabilitation and assistance. Given the magnitude of this problem and its societal ramifications, the time is ripe to explore the extent to which robotic devices can be used as a means of rehabilitation and assistance to improve the quality of life for the physically disabled.
In the last decade, robotic systems for rehabilitation, exoskeleton, and prosthetics have made significant advances. However, challenges lie ahead in their safety, size/weight, ease of use/don/control, and conformation to the societal norm.
In this discussion-oriented workshop, we invite leaders in this field to debate the great challenges of physical human-robot interactions for rehabilitation and assistance. Specifically, we will discuss the advantages/disadvantages of the currently available systems, safety mechanisms required for physical human-robot interaction, what must be developed/discovered in academia in the next 10 and 30 years, and what features are crucial for improving the quality of life for the physically disabled.

Workshop FRI3 *Intuitive Human-Robot Interaction for Getting the Job Done*
Woodlands Ballroom B

Geert-Jan M. Kruijff, German Research Center for Artificial Intelligence
Dirk Spenneberg, German Research Center for Artificial Intelligence
Frank Kirchner, German Research Center for Artificial Intelligence

Description:
Over the last couple of years, robots have been deployed well beyond the production line. The UN World Reports on robotics show marked increases in the number of household service robots, and we see practical uses of robots in e.g. search and rescue missions, and maintenance in underwater or planetary operations. An important consequence of this wider deployment is that robots are now more likely to interact with non-export users. This raises serious issues for human-robot interaction. How can we make interfaces that make it possible for a human to interact with one or more robots, so that the human can maximize exploitation of the robots' abilities? How can we make sure that these interfaces are easy to use, and make it possible for the human "to get the job done" rather than to wrestle the interface? Ultimately, the usefulness of a robot will depend on how easy it is to deal with it, to interact with it. Intuitive modes of interaction are thus likely to be a determining fact or in how well robots can be integrated into our working environments and social lives.
The goal of this workshop is to provide a platform for discussing methodologies for establishing, developing, and evaluating mission-dependent intuitive forms of human-robot interaction:

- What could be methodologies for establishing which types of human-robot interaction are useful ("intuitive to use") in a particular scenario? What shape do such experiments take, what metrics are available to test for significant behaviors? How could we make such results available to the wider community, in a reusable format?
- What could be methodologies for designing modular systems for human-robot interaction, to enable portability and reuse across robot platforms and mission domains? How could such design methodologies provide flexible means for adapting to different levels of user expertise, and to different interaction modalities?
- What could be methodologies for evaluating whether implemented forms of human-robot interaction are useful in a particular scenario? Again, what shape could such experiments take, what evaluation metrics are available?

Workshop FRI4 *Science and Technology Challenges for Robotics*
Woodlands Ballroom C & D

George Bekey (USC)
Vijay Kumar (UPenn)
Matthew Mason (CMU)

URL: http://www.grasp.upenn.edu/∼kumar/workshop/stc_workshop.html

Description:
Goal: The workshop will bring together leaders in academia, government and industry to identify and articulate key scientific and technological achievements in robotics, the main challenges confronting the community, and the key milestones for the next decade.
Background: Over 4 decades have passed since the installation of the first industrial robot, and the first robotics research conference was held over 2 decades ago. A recent study at www.wtec.org/robotics provides a good summary of the the state-of-the-art in robotics research and development. While the industry surrounding industrial and service robotics is only $10B world wide, the impact of robotics science and technology the goes well beyond this industry. Contributions of the robotics community ranging from algorithms for dynamic simulation and motion planning to designs for vehicles and robot platforms have had a significant influence on industries that are not identified with robotics. Students trained in robotics are attractive to both civilian and defense industry. Most universities, colleges and even schools have made or are making significant investments in robotics because of the intellectual foundations of the field. And yet funding for basic research in this field is low. The workshop will engage members of the community to identify and articulate key scientific and technological achievements and milestones for the future. Possible outcomes of the workshop include the establishment of a world-wide network in robotics, a decadal survey of robotics research, and a roadmap for investment in robotics.
Format: The workshop will consist of several talks by representatives from academic institutions, government agencies and industry, followed by discussions.

Workshop SAT1 *Robot Vision for Space Applications*

CANCELED

Workshop SAT2 *Socially Assistive Robotics*
St. Marks Room

Adriana Tapus, University of Southern California
Maja Mataric, University of Southern California

URL: http://robotics.usc.edu/interaction/rssws06/ws-SAR06.html

Description:
Research into Human-Robot Interaction (HRI) for socially assistive applications is still in its infancy. Various systems have been built for different user groups. For example, for the elderly, robot-pet companions aiming to reduce stress and depression have been developed, for people with physical impairments, assistive devices such as wheelchairs and robot manipulators have been designed, for people in rehabilitation therapy, therapist robots that assist, encourage and socially interact with patients have been tested, for people with cognitive disorders, many applications focused on robots that can therapeutically interact with children with autism have been done, and for students, tutoring applications have been implemented. An ideal assistive robot should feature sufficiently complex cognitive and social skills permitting it to understand and interact with its environment, to exhibit social behaviors, and to focus its attention and communicate with people toward helping them achieve their goals.
The objectives of this workshop are to present the grand challenge of socially assistive robotics, the current state-of-the-art, and recent progress on key problems. Speakers at the workshop will address a variety of multidisciplinary topics, including social behavior and interaction, human-robot communication, task learning, psychological implications, and others. The workshop will also cover a variety of assistive applications, based on hands-off and hands-on therapies for helping people in need of assistance as part of convalescence, rehabilitation, education, training, and ageing. The proposed workshop is aimed at providing a general overview of the critical issues and key points in building effective, acceptable and reliable human-robot interaction systems for socially assistive applications and providing indications for further directions and developments in the field, based on the diverse expertise of the participants.

Workshop SAT3 *Self-Reconfigurable Modular Robots*
Woodlands Ballroom A

Mark Moll, USC/ISI
Behnam Salemi, USC/ISI
Greg Chirikjian, JHU
Eric Klavins, U Washington
Hod Lipson, Cornell
Daniela Rus, MIT
Wei-Min Shen, USC/ISI
Mark Yim, UPenn

URL: http://www.isi.edu/∼moll/RSS06

Description:
Self-reconfigurable modular robots are metamorphic systems that can autonomously change their logical or physical configurations (such as shapes, sizes, or formations), as well as their locomotion and manipulation capabilities based on the mission and the environment at hand. Because of their modularity, versatility, self-healing ability and low cost reproducibility, such robots provide a flexible approach for achieving complex tasks in unstructured and dynamic environments. They are well suited for applications such as search and rescue, reconnaissance, self-assembly, inspections in hazardous environments, and exploration in space and oceans. They also pose fundamental research challenges for robotics and other major branches of computer science, mechatronics and control theory.
This workshop will discuss the grand challenges for self-reconfigurable modular robots and possible approaches to tackle these challenges. These challenges can be organized into the following partially overlapping themes:

- Self-repair and self-replication: modular robots have the unique capability to recover from damage and replicate structures. One of the biggest challenges is to create practical algorithms that take advantage of this capability.
- Limited resources: modular robots are limited by power, size, torque and other resources. One of the main challenges here is to improve battery density and fuel storage for modules.
- Scale: algorithmic and physical limitations make it difficult to scale to a large number of modules and to very small modules. Reliability also becomes an important issue as the number of modules increases or the size decreases. We can define milestones along these scales, such as:
  - Build a self-reconfigurable machine with $>$100 modules
  - Build a self-reconfigurable machine with $<$1cm modules
  - Build a machine that can operate unattended for X days or recover from Y% damage
  - Develop planning algorithm that will work on $>$1E6 units in real time (assuming realistic physical, computational, and communication capacity of modules)
- Hardware: the planning and control side of self-reconfigurable modular robots are far ahead of the hardware side, despite many brilliant and novel ideas. We will address the general hardware issues (including power, connectors, structural strength) that will lead to real and compelling applications.

Workshop SAT4 *Manipulation for Human Environments*

Woodlands Ballroom B

Charles C. Kemp, MIT
Aaron Edsinger, MIT
Paul Fitzpatrick, University of Genova
Lorenzo Natale, MIT
Eduardo Torres-Jara, MIT

URL: http://manipulation.csail.mit.edu/rss06/

Description:
The aim of this workshop is to explore modern approaches to robot manipulation in human environments. There is a resurgence of interest in robot manipulation as researchers seek to push robot manipulation out of controlled factory settings and into the dynamic and unstructured world we inhabit. Robots that successfully manipulate the spaces we inhabit will require new mechanisms and methods for perception and control. This workshop will investigate promising approaches that address the challenges of general manipulation within these domains.
Key issues which must be addressed include: safety, human-robot interaction, robustness to uncertainty, and generalization over tasks.
This workshop will serve as a successor to the Workshop on Humanoid Manipulation from RSS 2005. Although humanoids are well-matched to human environments, other form-factors may be advantageous. The unifying theme of this year's workshop will be robust operation within human environments.

Workshop SAT5 *Workshop on the DARPA Grand Challenge: Progress and Perspectives in High-Speed Autonomous Robotics*
Woodlands Ballroom C & D

Chris Urmson, CMU
Mike Montemerlo, Stanford
Richard Murray, Caltech
Ron Kurjanowicz, DARPA
Stefano Soatto, UCLA
Sebastian Thrun, Stanford

Description:
The 2005 DARPA Grand Challenge proved a compelling demonstration of the state-of-the art in high-speed autonomous navigation. The goal of this workshop is to present the key ideas and innovations that made the 2005 Grand Challenge a success and to also highlight research relevant to the 2007 Grand Challenge which may emphasize driving in traffic.

Workshop SAT6 *Grand Challenges of Micro and Nanoscale Robotics*
Regent Room

Metin Sitti, Carnegie Mellon University
Bradley Nelson, ETH Zurich

Description:
For the miniaturization of devices and machines down to nanometer sizes, micro/nanorobotic approach enabling manipulation, locomotion, and interaction at the micro and nanoscales is indispensable. Micro/Nanorobotics as an emerging robotics field is based on the micro/nanoscale physics, fabrication, sensing, actuation, system integration, and control taking the scaling effects and nanoscale physics and chemistry into consideration. Micro/Nanorobotics encompasses: (i) programmable assembly of micro/nanoscale components; (ii) design and fabrication of miniature robots with overall dimensions down to sub-millimeter ranges and made of micro/nanoscopic components; and (iii) programming and coordination of large numbers of micro/nanorobots.
This full-day workshop would address the grand challenges of this newly emerging micro/nanorobotics area. We plan to allocate a large portion of the workshop for discussions of current challenges, potential solutions, and future directions of micro/nanorobotics. Leading researchers from USA and Europe would give 30 minute talks (including 10 minute discussions) and many open discussion sessions would be held for an interactive and productive workshop.

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Author Instructions

The conference proceedings for *Robotics Science and Systems* will be published as a book by MIT Press. The final version of your paper and all other information necessary for its publication will be due on September 22, 2006. Please incorporate feedback you received at the conference into your final submission. Please read these instructions carefully to avoid delaying the publication of the proceedings.

1. **Title and Authors:** If the title or authors for your paper have changed since you submitted your information in January, please email the updated information as soon as possible to

   rss-submissions-06@cs.washington.edu

   using "RSS info change <number>" in the subject line, where <number> is your paper number as it appears in this conference booklet.

2. **Author Agreement Form:** One author must complete and sign the author agreement form, which appears on page 75 of this booklet (also available for download from the *Robotics Science and Systems* homepage). Please mail the original, signed author agreement form to the following address by September 22, 2006:

   Robotics Science and Systems c/o Dieter Fox
   101 Allen Center
   Department of Computer Science & Engineering
   University of Washington
   Seattle, WA 98195, USA

3. **Formatting:** Please prepare your final submission according to the IEEE Transactions formatting requirements. A corresponding Latex class file can be obtained from the *Robotics Science and Systems* Web site: http://roboticsconference.org/robotics_template.tgz. Please do not modify the formatting provided in these files. Any change to font sizes, page dimensions, line spacing, etc. will delay the publication of your paper. Please do not include any additional markings such as "Draft" or "To appear in..." on the pages. Papers will be limited to 8 pages. Robotics Science and Systems offers no provision for accommodating papers that do not meet these requirements.

4. **Creating PDF files:** Delays in the production of proceedings are usually caused by the submission of PDF files that did not embed all fonts. Please follow these simple instructions to ensure that the PDF file you submit does not have this problem.
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   Checking the PDF file: Before you submit your file, please open it in Acrobat Reader. In the menu "File" under "Document Properties" you can find information about "Fonts." Your document should only contain Type-1 fonts. If you followed the instructions above, but your documents contains other types of fonts, they may have been included as part of figures. Please ensure that your submission only contains Type-1 fonts. If you experience difficulties creating PDF files that comply with this requirement, please send email to rss-submissions-06@cs.washington.edu prior to the deadline.

5. **Submission:** Please submit your paper by September 22, 2006, 9pm GMT using the link

   http://robotics-conference.confmaster.net

   We are looking forward to receiving your final submission!

Author Checklist

- Revised paper uploaded via the conference submission software
- Author agreement form signed and mailed to Dieter Fox via physical mail.
- If title or authors have changed, notify `rss-submissions-06@cs.washington.edu`

Please note: *We reserve the right not to publish accepted papers should not all information be received by September 22, 2006. We will also exclude papers that violate our formatting guidelines.*

Deadline is September 22, 2006.

Contributing Authors' Letter of Agreement

(must be completed by contact author, one per paper)

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For the purpose of publication of the above article in the book tentatively entitled

Robotics Science and Systems II

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ROBOTICS SCIENCE AND SYSTEMS 2007

Robotics Science and Systems 2007

Robotics Science and Systems 2007 will take place at the Georgia Institute of Technology and is tentatively scheduled to occur June 27-30, 2007. The conference will be chaired by Wolfram Burgard from the University of Freiburg, Germany. The Program Chair of Robotics Science and Systems 2007 will be Oliver Brock from the University of Massachusetts, Amherst.

Further announcement will be made on the permanent Web site of the conference.

`www.roboticsconference.org`

The RSS Conference Philosophy

RSS strives for the highest standards in its paper selection process. All reviewing of RSS papers is double-blind, meaning that the identity of a paper's author(s) is withheld from its reviewers. Proactive efforts are made to ensure that reviewers provide detailed comments back to the authors. In 2006, a rebuttal phase was added which allowed authors to comment on reviews before the area chairs made their final decisions.

The threshold for accepting poster and oral presentation is identical. As in the final proceeding, there is no distinction between oral and poster presentations. In fact, none of the chairs (general chairs, program chairs, area chairs) are eligible for an oral presentation. Their accepted papers are automatically assigned to the poster session.

In composing the conference program, RSS applies no bias with regards to the geographic origin of a paper. Instead, all selection decisions are purely based on the quality of the contribution. The number of submissions between the three primary geographic regions (Europe, Asia, Americas) varied widely in 2006, which is reflected in the final program. For 2007, RSS strongly solicits submissions from underrepresented geographic areas.

At RSS, individuals in the organizational structure revolve relatively quickly. Area chairs are expected to serve for no more than two years, to ensure a proper infusion of new talent into the main decision making body. Other executive positions have a one year term limit. The PC chair(s) has authority over composing the PC and the selection of papers and invited speakers. The program chair will become the general chair in the next year, to ensure continuity.

This conference makes zero profit. In fact, RSS has worked hard to make the conference affordable for everyone. To this end, the conference has been held at university campuses to reduce the overall cost. Special dorm space has been made available for affordable student housing, and various companies have generously contributed funds to further reduce the cost of participation. In 2006, we happily report an early student registration fee of only $100. This includes the participation in the conference banquet! This is four days of exciting robotics research and social events for just $100 (or $300 if you are not a student).

RSS is happy to announce that the IEEE Robotics and Automation Society (RAS) continues its technical co-sponsorship in 2006. In 2006, we also gained technical co-sponsorship from the International Federation of Robotics Research (IFRR). RSS continues to maintain a highly constructive working relationship with these established organizing bodies in the field of robotics.